A NEW CONCEPT IN FILM BADGE DESIGN

J. D. EASTES, M. L. MAURER and F. L. PASCHAL
Dynamics Corp., Fort Worth, Texas, U.S.A.

Abstract—Unique concepts are incorporated into a new personnel monitoring badge which include (1) a basic structural design to permit various options in the choice of dosimetric accessories, (2) unusual mechanical features for operational improvements, and (3) a specific film-filter system and an unusual new technique for dealing with the film energy dependence problem.

The basic structure of the badge consists of three molded plastic components which can be assembled or disassembled in a matter of seconds. When assembled the structure is locked together with a tamper-proof locking system. The components are designed to collectively contain two dental size film packets in separated compartments (each opposed by matched filter systems), a system of high range dosimetry devices in two other compartments, and identification and/or security credentials. The high range dosimetry compartments and the areas designated for the filter system are designed to afford numerous options in the choice of components for these systems. Individualized film compartments permit the use of either one or two film packets in the badge and make possible the selective exchange of film packets in a simple manner. A unique locking device serves a dual purpose as a lock when the badge is closed and as a catch which prevents the complete disassembly of the components when the badge is being serviced. The locking system is also unique in that only one magnet is required to open the badge even in automated operations. A specific filter system which consists of five different filters is utilized to accomplish routine dosimetry for beta, gamma, X-, thermal neutron and fast neutron radiations. Dosimetry for beta, gamma, X-, and thermal neutron radiations is accomplished with the same film. The major problem in film dosimetry, energy dependence, is treated in a unique new manner with this filter system, which permits the evaluation of mixed exposures involving photon radiations in the critical energy region with greatly improved accuracy. The technique utilizes an energy index factor which is the ratio of the sum of densities behind two filters to the sum of densities behind two other filters. The photon dose in the critical region is determined from the sum of the excess densities behind three relatively thin filters as compared to a thicker filter, using the apparent energy indicated by the index factor. The density under the thick filter in excess of that predicted for the apparent exposure in the critical energy region is attributed to high energy photons. The filter system and techniques related to those just mentioned permit the evaluation of mixed exposures involving the four types of radiation mentioned previously.

A simple mathematical development of the energy index and low energy dose factors are presented and the film dosimetric capabilities attainable with the system have been verified with appropriate testing; however the test results are not included in this report. The badge has been in use since January 1965 and has proven very satisfactory in routine use and in the evaluation tests. The test results show that the film dosimetry capabilities attainable with the system described greatly exceed proposed standards.

INTRODUCTION

During the past two decades the film badge has continued to be the principal means of (external) personnel monitoring. As a result of ever-increasing requirements, both monitoring and otherwise, the film badge has evolved into a multi-purpose system of credentials and dosimetric devices. Unfortunately this evolution has not resulted in a standard system.

In general, badge structures have been designed to accommodate the particular system of components available at that time, which most nearly satisfied the requirements of the designer. Too often it has been necessary to design a new badge, or to resort to multiple badges in order to improve personnel monitoring capabilities, or to satisfy new requirements.

In January 1965, the Fort Worth Division of General Dynamics put a new badge design into routine service which continues the evolution of the film badge into a combination monitoring and identification system. The badge represents a significant change in design concept in that the structural components can accommodate a wide variety of choices of paraphernalia for identification and monitoring purposes. Thus, the structure does not limit the system to its current status, but is adaptable to changes which satisfy new requirements, or which improve the state of the art. The badge structure is presently complemented with a diverse array of accessory components which represent current trends, including an unusual approach to the film energy dependence problem.

This paper describes the badge as equipped for use at the Fort Worth Division of General Dynamics, with occasional reference to unique features and to the features which permit unusual options.

STRUCTURAL COMPONENTS

The structural components of the General Dynamics badge are shown in Fig. 1. The three major components will be referred to as the Rear Component, the Dosimeter Holder and the Front Component. These three components are designed to lock together to form a unit which houses the entire monitoring system. (The assembled badge measures 8.3 cm $\times$ 5.3 cm $\times$ 1.2 cm and weighs approximately 60 g when fully equipped.)

The *Rear Component* composes the back, the top, and both side portions of the badge. Part of the front side of this component is slightly indented to accommodate the rear array of filters. With the exception of the open window and the plastic filter, this design permits some option as to the choice, size, and orientation of the filter array. A long slender strip of spring steel is mounted at one end in a cavity on the right side of this component. This strip has a 90° bend at its free end which permits a small portion of the spring to emerge through a slot into the space occupied by the dosimeter holder and thus to act as a catch or locking device. A clip, which is free to rotate, is attached to the rear side of this component.

The *Front Component* is designed to slide into a groove in the side and top portions of the rear component and thus compose the front side of the badge structure. An array of filters which match those on the rear component is mounted on the back side of this component

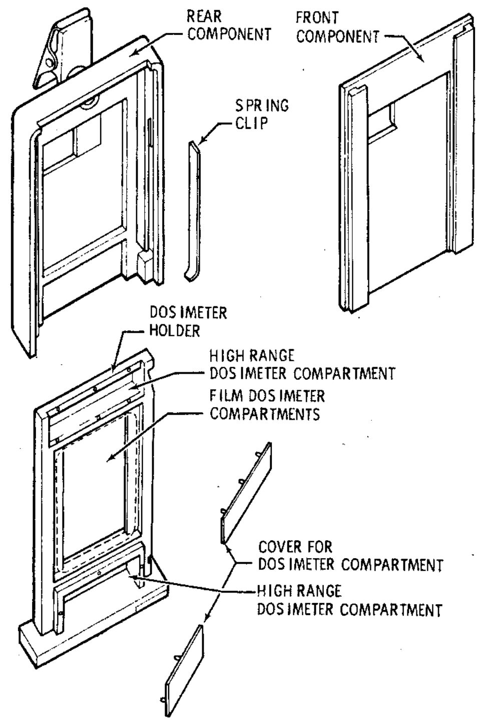

FIG. 1. Structural components of the General Dynamics film badge.

in an indented area which provides the option previously mentioned. The front side of this component also has a slight indentation over the entire film area so that a lead identification tape can be affixed in any desired position and orientation. The front side of this component is designed to accept a 15 column identification-time card or other appropriate credentials. These credentials may be inserted into slots constructed on each side of the front from either the top or bottom when the badge is open.

The credentials can be inserted or removed only from the top when the badge is closed. (With a slight modification of the molds the credentials can be locked in place when the badge is locked.)

The *Dosimeter Holder* is designed to contain the high range monitoring devices and to transport and confine two film packets to their particular location within the badge. This component also composes the bottom of the badge and functions as an integral part of the locking system. The high range dosimetry devices are housed in two rectangular shaped compartments or cavities which are covered with removable clear plastic covers. The compartment at the bottom end of the holder measures 2.70 cm × 1.11 cm × 0.55 cm. The other compartment is located at the top end of the holder and measure s3.49 cm × 0.87 cm × 0.24 cm. The high range dosimetry devices selected for use at the Fort Worth Division are compactly located in these compartments by means of small molded plastic packaging components fabricated to contain each particular device. Any other system of high range devices which are within the size and shape limitations of the compartments can be incorporated into the badge by merely fabricating new packaging components. (This is the second unique option of the design.) The holder is designed to accept either *one* or *two* film packets in the center portion of the unit and to transport and confine the film to its proper location within the badge regardless of whether one or two packets are used. Each packet is confined to its portion of the holder by the walls of a frame-like opening in the center of the holder and by thin separators which protrude from each of the two side walls into the space between the packets. (This is the third unique feature.) The front and rear components serve as the remaining structures which confine the packets when the badge is assembled.

The design features just mentioned make it possible to selectively exchange the packets in a rather simple manner. If the holder is withdrawn from the badge assembly with either *face* directed in the vertical direction the film packet on the opposite side will fall from the holder while the top packet will be retained. (Either packet can thus be removed by this procedure.) When the holder is withdrawn with either *edge* of the badge directed vertically both packets will fall from the badge *but from opposite sides*. Thus, packets can be selectively exchanged, or can be collected separately at exchange time by means of a simple collection system positioned beneath the badge when it is opened.

The right side of the dosimeter holder is designed to function as part of the locking mechanism. There is a small narrow gap across this side near the bottom of the holder and a notched gap near the top. When the structural components are assembled in the closed position the free end of the thin spring which is mounted in the rear component protrudes into the bottom gap; thus, any force which tends to remove the holder results in a shearing force upon the spring. The second (notched) gap serves to retain the holder in the badge while it is being serviced, yet permits the badge to be closed and locked by mechanical action. This two-stop locking feature is designed for use with a single permanent (or electro) magnet. When the right edge of the badge is drawn through a sufficiently strong magnetic field the free end of the spring will be withdrawn from the gap in the holder. As the badge is drawn across the gap of the magnet the field will retain the holder by the attractive force exerted on the soft iron bar which is mounted at the corner of the badge in the bottom of the dosimeter holder. When the body of the badge is drawn far enough to remove the spring from the magnetic field the free end of the spring will ride along the side of the holder until it engages the second catch (i.e. the notch gap). Further movement of the badge in the same direction will remove the iron bar from the magnetic field. The badge can be closed and locked by reversing the direction of motion just described, or by simply pushing the holder into the closed position. The holder may be withdrawn completely from the badge by application of the magnetic field to the spring a second time when the badge is opened. This permits complete disassembly (or assembly without the use of a magnet) of the three structural components in less than ten seconds. All the internal components of the badge and dosimetry system are completely accessible when the badge is disassembled.

ACCESSORY COMPONENTS

Various accessories have been incorporated into the badge structure to fulfill present requirements. These requirements and the applicable components are as follows:

Identification: The identification credentials consist of currently acceptable data printed on colormatch paper and enclosed in a clear plastic envelope. This envelope is located in the front component of the badge structure in grooves at each side which are designed to accept either of the following devices: a 15 column identification-time card; a thick printed form for visitor identification; the credentials just described; any other credential of the appropriate size. The printed form for visitors is retained as part of the personnel monitoring records. X-ray is used to permanently identify the film with a number engraved through a thin lead tape (0.64 cm × 3.02 cm × 0.014 cm) which is affixed to the front component immediately below the filter system. The date can also be X-rayed into the film (below the identification number) with a similar tape appropriately positioned in the X-ray shield.

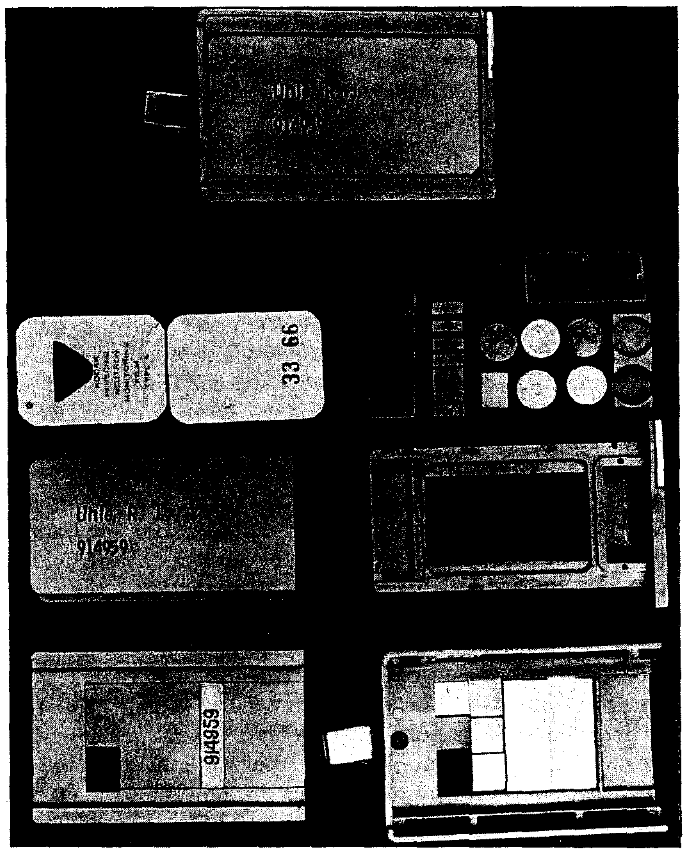

FIG. 2. Front views of the badge; disassembled and assembled.

Routine monitoring accessories: Routine monitoring accessories consist of two film packets, two matching sets of five filters each, one set each bonded to the front and rear components, and the identification tape just described. The two film packets are Dupont's Type 544 X-beta-gamma packet and Kodak's Type A Personal Neutron Monitoring Film packet. The filter materials are aluminum (Al), thin iron (Fe_1), thick iron (Fe_2), tin (Sn), and cadmium (Cd), plus the plastic (Pl) and open window

(OW) which are part of the structural design. The characteristics and location of the filters are given in Fig. 2 and Table 1. The routine monitoring system is designed to render information which may be used for the interpretation and evaluation of beta, gamma, X-ray, thermal-neutron, and fast neutron exposures, whether present concurrently or independently. The position and orientation of the filter system are shown in Fig. 3. There are several reasons for the size and arrangement of the filters. The evaluation of fast neutron exposures is accomplished by the track counting method described by Cheka and others.[1-3] At our facility the track counting is accomplished by means of a projection microscope. The special film holder used during the counting operation will not permit the positioning (or movement) of the microscope objective to the edge of the film. It is also desirable to move the objective in long sweeps across the film during the counting operation rather than a short, bi-directional path. Finally it is highly desirable to provide a Cd shielded area on the neutron film that is large enough to locate easily and to operate within during the reading operation. Thus a large cadmium filter was chosen and positioned near the center of the packet. With the exception of Cd, the filters were chosen large enough to reduce scatter into the center portion of the film behind the particular filter to an acceptable minimum and large enough to be easily positioned in the density reading device (densitometer), yet small enough to fit compactly in the space available in the badge. The filters are mounted close together in a compact array which extends slightly beyond the outer edge of the film packets. This arrangement is an attempt to reduce scattering of radiations into the film behind the filters, a problem of considerable importance.[4]

The Al and Fe_1 filters were experimentally

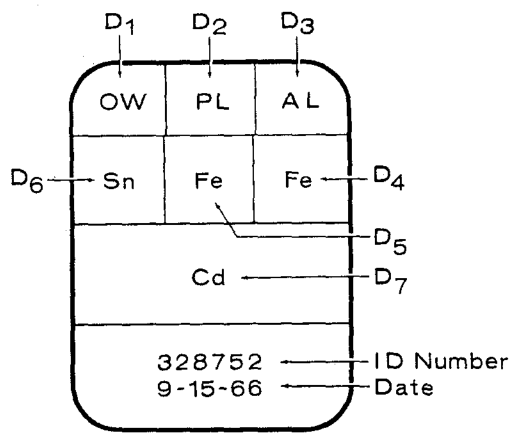

FIG. 3. Position and orientation of the filter system with respect to the film.

matched using both natural Uranium and ^{90}Sr to achieve identical attenuation of beta radiation. High energy photons ($E > 250$ kVe) are also attenuated identically; however, the pair differ significantly in low energy photon attenuation properties. (Henceforth low energy photons will be assumed to be in the $30 < E <$

Table 1. Physical Characteristics of the Filter System

Filter material	Surface dimensions (cm)	Thickness (mm)	Total Mg/Cm² thickness*
Open window	0.953 × 1.27	0	39
Plastic (cycolac)	0.953 × 0.953	2.70	343
Aluminium	0.953 × 0.953	0.84	407
Iron	0.953 × 0.953	0.25	376
Iron	0.953 × 1.03	0.71	728
Tin	0.953 × 1.03	1.14	1013
Cadmium	1.27 × 3.18	0.97	1018

* Includes filter, plastic structure, and identification materials.

250 kVe energy range.) Thus the film response behind these two filters may be conveniently used to detect the presence of low energy photon radiation in an exposure. The Sn and Cd filters were also matched experimentally to produce identical attenuation of high energy gamma radiation. When exposed to thermal neutrons the (N, γ) reaction $(E_{\gamma eff} = 2.18 \text{ meV})$ in the Cd filter results in a significant increase in the exposure to the Dupont film behind that filter whereas no appreciable change in exposure will be noted behind the Sn filter. Thus the difference in density behind the matched (Cd: Sn) pair of filters is a measure of the thermal neutron exposure received by the badge. The density produced behind the Cd filter has been reported to be related to the density produced by gamma rays by the ratio $\frac{\text{roentgens } (\gamma)}{\text{rem}(N_{th})} = \frac{\text{density } (\gamma)}{\text{density } (N_{th})} = 1.98$;[5] however this ratio may be subject to the cadmium ratio of the neutron spectrum.[6] Tin was chosen as the material to match Cd (1) because its backscatter properties are very similar to those of cadmium and (2) because its absorption edge is below 30 kV. With regard to (1) in the previous statement, it should be noted that if the sensitive component of a film packet is positioned near the surface of a filter system and the badge exposed to photons from the rear rather than the front, the backscatter from dense metal filters such as cadmium, lead, etc., increases the film density in the areas adjacent to them.

The amount of backscatter varies with the filter material and as a result can erroneously indicate a thermal neutron exposure if two filters differ significantly in backscatter properties. Al, Fe, and Sn were all chosen as filter materials because of their low absorption edge, their density, mechanical, and other favorable properties.

High range monitoring components and accessories: The high range monitoring system is patterned after the system which originated at Hanford[7] and consists of a bare indium foil, and a cadium covered indium foil, a sulfur pellet, and a bare copper bar. Provisions have been made for the use of either glass rods or thermoluminescent dosimetry (TLD) materials in addition to the foils and pellets. Recent developments in the TL dosimetry[8] indicate that a TLD system will be a desirable addition to this system. A thick indium tape affixed to the rear component just below the array of filters is also a part of the high range dosimetry system. The physical characteristics of the high range system are exhibited more completely in Tables 2 and 3.

Miscellaneous: The badges are serviced, transported, and stationed for use on racks which are designed to hold 56 badges each (along with 56 pocket dosimeters). The racks are of a step-like construction and are designed to display the entire front of each badge for ease in locating any particular badge. This construction also permits permanent identification of the film in lots of 56 badges each by use of a similarly fashioned lead shield which has

Table 2. Physical Characteristics of the High Range Neutron Dosimetry Components

Dosimetry component	Area (cm × cm)	Thickness (cm)	Weight (g)	Number used	Location and exposure condition
Indium	1.175 × 3.1	0.0381	1.02	1	Rear component below cadmium (film) filter
Indium	1.13 Dia. (disc)	0.0254	0.189	2	Lower cavity—one behind sulfur pellet (bare), one sandwiched between two cadmium discs
Copper	0.92 × 1.1	0.106	0.799	1	Upper cavity—bare
Sulfur	1.116 Dia. (disc)	0.30	0.585	1	Lower cavity—in front of bare indium foil
Cadmium	1.129 Dia. (disc)	0.055	0.468	2	Lower cavity—on either side of an indium foil

windows that are accurately positioned in front of the lead tapes when the shield is placed over a rack.

ROUTINE MONITORING

The evaluation procedure for routine monitoring of X-ray (low energy photons), gamma rays (high energy photons), beta particles, and thermal neutron exposures involves the various densities produced in the Dupont film. The film response (net transmission density versus exposure) to either of these radiations is relatively linear over most of its useful range and thus it is not unreasonable to assume that its response to combinations of these radiations is also approximately linear.

Assuming that the film response is relatively linear to exposures involving individual and multiple radiation types over most of its useful range the following linear equations may be used to represent the densities in the various filter areas:

$D_1 = b_1B + x_1X + g_1G =$ *the net density in the OW area.*

$D_2 = b_2B + x_2X + g_2G =$ *the net density behind the Pl filter.*

$D_3 = b_3B + x_3X + g_3G =$ *the net density behind the Al filter.*

$D_4 = b_4B + x_4X + g_4G =$ *the net density behind the thin Fe filter.*

$D_5 = b_5B + x_5X + g_5G =$ *the net density behind the thick Fe filter.*

$D_6 = b_6B + x_6X + g_6G =$ *the net density behind the Sn filter.*

$D_7 = b_7B + x_7X + g_7G + kN_{th} =$ *the net density behind the Cd filter.*

where b_n, x_n, g_n, and k represent the net density per unit dose of beta, X-$_1$ gamma- and thermal neutron radiations respectively, and B, X, G, and N_{th} represent the beta, X-ray, gamma-ray, and thermal neutron dose respectively. The subscript (n) is used to represent the various areas. The filters were chosen such that $b_3 = b_4$, $b_5 \cong b_6 \cong b_7 \cong 0$, and $g_3 \cong g_4 \cong g_5 \cong g_6 \cong g_7$.

Table 3. Analysis of High Range Neutron Exposures

Neutron energy range	Dosimetry component utilized	Cross-section (barns)	Half-life	Method of analysis	Corrections required
0.025 eV to 0.3 eV	In	145	54.3 m	Use activity difference between bare and cadmium covered indium foils.	Backscattering and cadmium absorption.
0.3 eV to 2 eV	In	28,000*	54.3 m	Use activity of cadmium covered indium foil.	None.
2 eV to 1 MeV	Cu	0.09	12.8 hr	Positron annihilation gammas (510 keV) counted. (A 657 keV positron is emitted by 19% of Cu-64).	Thermal and epithermal activation.
1 MeV to 2.9 MeV	In	0.18	4.5 hr	Count cadmium covered indium (either 0.335 MeV gammas or 0.96 MeV betas) for activity produced by inelastic scattering of fast neutrons.	Activity due to fast neutrons of energy above 2.9 MeV
2.9 MeV up	S	0.23	14.5d	Count 1.71 MeV betas from P^{32} produced in the S^{32} (n,p)P^{32} reaction.	None.

* At 1.4 eV resonance.

It should be noted that it is not necessary to utilize all of these equations in a particular analysis and that by a judicious choice of filters the analysis of exposures can be simplified. Therefore, the filter system was chosen such that $b_3 = b_4$ and $b_5 \cong b_6 \cong b_7 \cong 0$ (that is, the filters were chosen for identical beta response behind the Al and thin Fe filters and essentially no beta response behind the other three metal filters) and such that $g_3 \cong g_4 \cong g_5 \cong g_6 \cong g_7$ (that is, essentially equivalent gamma response behind the five metal filters).

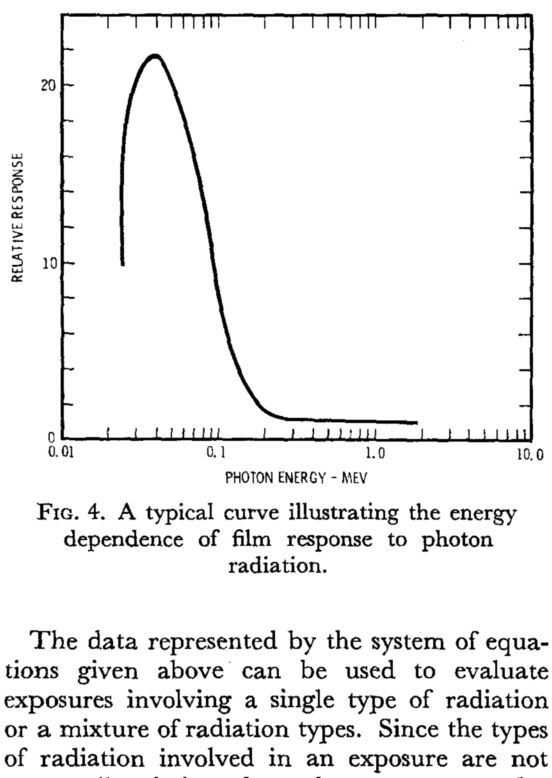

FIG. 4. A typical curve illustrating the energy dependence of film response to photon radiation.

The data represented by the system of equations given above can be used to evaluate exposures involving a single type of radiation or a mixture of radiation types. Since the types of radiation involved in an exposure are not necessarily obvious from the appearance of a processed film it is necessary to proceed from the complicated to the simple in devising a technique for analysis of an exposed film. Fortunately in many cases it is possible to circumvent a lengthy analysis by use of knowledge either of the potential types of exposure or the history of the subject's activities during the period in which the film was exposed. In such cases the appropriate simplified analysis can be applied immediately.

Analysis of exposures involving (X, B, G) *radiations*: The most important particular problem in film dosimetry is the energy dependence of film response to low energy photons. A typical energy dependence curve for film is shown in Fig. 4. To overcome this problem it is necessary either to ascertain the energy of the photon radiation or to reduce the energy dependence of the film to an acceptable level by attenuation of the incident photon radiation. Either alternative can be used to accomplish a satisfactory analysis procedure; however, the former affords at least two advantages: (1) some information is acquired regarding the photon spectrum (thus the system serves as a simplified spectrometer) and (2) the sensitivity of the detector is preserved. The system described in this report is designed to apply to the former approach to the problem. The first requirement in the analysis of an exposure then is to determine the energy of the low energy component of the incident photon radiation. This determination can be accomplished quite easily by use of the energy index factor, K, which is derived from four of the basic density equations as follows:

Consider the ratio:

$$\frac{D_3 + D_4}{D_5 + D_6} = \frac{(b_3 + b_4)B + (x_3 + x_4)X + (g_3 + g_4)G}{(b_5 + b_6)B + (x_5 + x_6)X + (g_5 + g_6)G}$$

Now $(b_3 + b_4)$ is very small compared to $(x_3 + x_4)$ and for all practical purposes may be neglected. Also b_5 and b_6 are approximately zero and $g_3 \cong g_4 \cong g_5 \cong g_6$ by design, so that the ratio reduces to:

$$\frac{D_3 + D_4}{D_5 + D_6} = \frac{(x_3 + x_4)X + 2\,g_6G}{(x_5 + x_6)X + 2\,g_6G}$$

Now if $G = 0$ (i.e. there is no high energy photon component of exposure) the ratio reduces to:

$$\frac{D_3 + D_4}{D_5 + D_6} = \frac{(x_3 + x_4)X}{(x_5 + x_6)X} = \frac{(x_3 + x_4)}{(x_5 + x_6)} = K$$

where K is a constant which depends only on the low energy photon energy. (It should be noted that K can be used to determine the energy of low energy photons even when $G \neq 0$

provided G is not too great, because $(x_3 + x_4) >> 2g_6$.)

Calibration data at six energies in the 30–215 kVe (kilo-volt-effective) range have been used to produce the smooth curve of K versus energy shown in Fig. 5.

The slope of this curve indicates good resolution of energies up to approximately 150 kVe. It should be noted that K can be used to

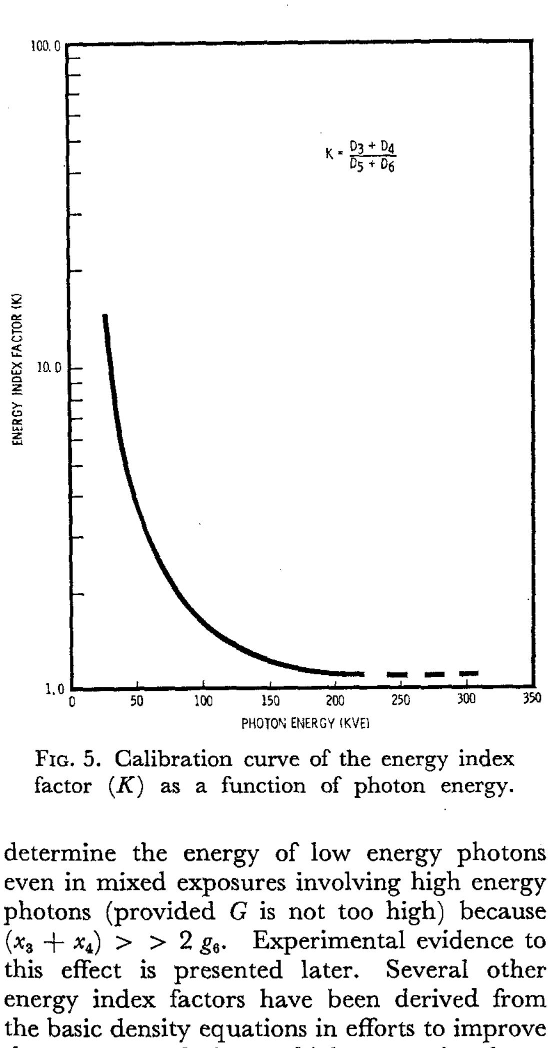

FIG. 5. Calibration curve of the energy index factor (K) as a function of photon energy.

determine the energy of low energy photons even in mixed exposures involving high energy photons (provided G is not too high) because $(x_3 + x_4) >> 2\,g_6$. Experimental evidence to this effect is presented later. Several other energy index factors have been derived from the basic density equations in efforts to improve the energy resolution at higher energies; however, these have generally resulted in curves which give ambiguous results (i.e. the slope becomes positive due to significant scattering contribution to the low densities which occur at the higher energies). Once the effective energy of the low energy photon radiation has been established there still remains the problem of independent determination of the dose contributions by each of the radiations involved in mixed exposures. The normally accepted procedure for determining the high energy and low energy photon contributions to an exposure is to assume that the density behind a thick filter (such as the Sn filter) is due entirely to high energy photons and to use that density (D_6) to determine the high energy photon dose. The high energy dose is then used to predict the "expected" density behind a thin filter (such as the Al) and the difference in the expected and actual densities used to determine the low energy photon dose. The major fallacy in this approach is that it depends upon the assumption that x_6X is zero, that is, that there is no low energy photon contribution to the density behind the thick filter. There is in fact a significant contribution to the density behind the Sn filter because, even though the low energy spectrum is attenuated and hardened by the filter, the emulsion still exhibits a very significant response due to its energy dependence. As a result the high energy component of the exposure (and thus, the total photon exposure) will be greatly exaggerated if such a procedure is used. For example, the density behind Sn for a 200 mr exposure to 120 kVe X-rays is approximately 0.50 net density units. If taken from a ^{60}Co curve this density indicates an exposure of approximately 450 mr. If the normally accepted procedure is used the evaluation would indicate a dose of 450 mr *plus* whatever low energy dose the procedure yields, and thus the result would be a gross over evaluation of the exposure.

This problem can be circumvented by reversing the procedure, that is, by determining the low energy dose first and then determining the high energy dose. The low energy dose can be determined relatively independent of the contribution of the other components of the exposure by use of a low energy dose factor, D_L, which is derived from three of the basic density equations as follows:

Consider the sum of density differences:

$$(D_3 - D_6) + (D_4 - D_6) + (D_5 - D_6) = (D_3 + D_4 + D_5) - 3D_6$$

By substitution of the original density equations and collection of terms this becomes:

$$(b_3B + x_3X + g_3G) + (b_4B + x_4X + g_4G) + (b_5B + x_5X + g_5G) - 3(b_6B + x_6X + g_6G) = (b_3 + b_4 + b_5 - 3b_6)\,B + (x_3 + x_4 + x_5 - 3x_6)X + (g_3 + g_4 + g_5 - 3g_6)G.$$

For all practical purposes $b_5 \cong b_6 \cong 0$ and $b_3 + b_4$ is very small compared to the coefficients of the X term; thus the first term (involving B) may be neglected. Also since $g_3 \cong g_4 \cong g_5 \cong g_6$ the coefficient of the term involving G is approximately zero and the equation reduces to: $(D_3 + D_4 + D_5 - 3\,D_6) = (x_3 + x_4 + x_5 - 3\,x_6)X = AxX$ (where Ax is a constant), which shows that the sum of densities originally stated is a measure of the low energy photon dose. Thus we have a low energy dose factor which we shall designate as D_L, where

$$D_L = (D_3 + D_4 + D_5 - 3\,D_6)$$

The nature of D_L is more apparent in Fig. 6 where D_L versus exposure is shown for six X-ray energies. A comparison of these curves with a set of curves (density versus exposure) produced for any *one* of the basic density equations (with $G = B = 0$) reveals two significant differences: (1) the range of density values for D_L is over three times as great as either of the basic density ranges and (2) the curves for the various energies are more widely separated with some apparent improvement in resolution of points about the individual curves (probably due to the counter-balancing effect of multiple density readings on errors inherent in individual density readings which are attributable to non-uniformity of the film, scatter effects, reader errors, etc.). Once the energy and dose due to the low energy photon radiations have been determined the expected Sn density can be determined from curves similar to those shown in Fig. 6. The high energy photon dose, G, can be determined from the (Sn — Sn_e) density difference. Finally, the beta dose, B, may be roughly

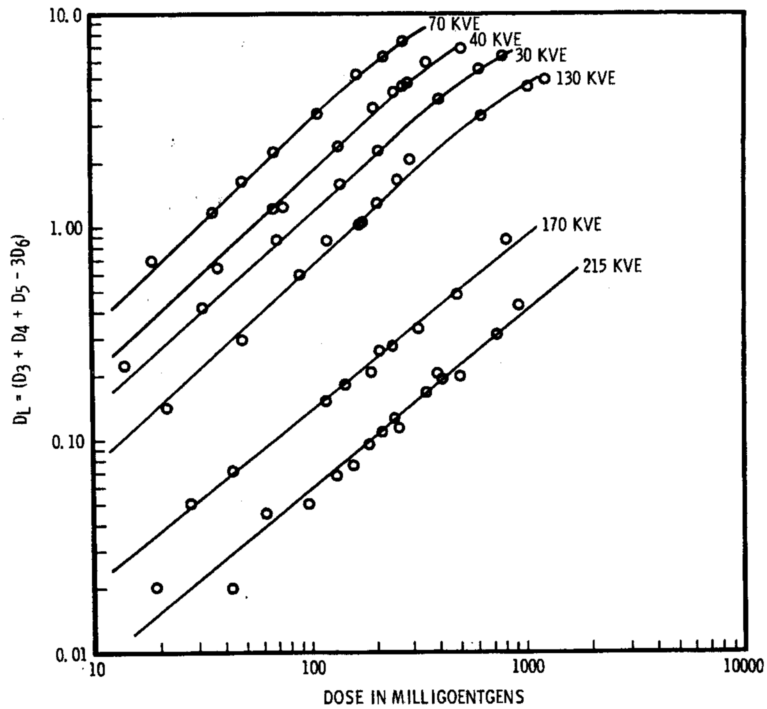

FIG. 6. Typical calibration curves for the low energy dose factor (D_L).

estimated from the difference between the OW or Pl (D_1 or D_2) density and the sum of the expected densities due to the X and G exposures; however, the cautions presented later regarding such an interpretation should be noted. Evaluation of exposures involving only one or two of the three types of radiation may be summarized as follows: $(X + G)$—evaluate as previously described, but eliminate the B evaluation procedure; $(G + B)$—evaluate G from the Sn

Analysis of exposures involving thermal or fast neutrons: Thermal neutron exposures may be evaluated by use of appropriate measures of the responses of either the Dupont or the Kodak film components. Use of the Dupont film response is preferable because of the relative ease, simplicity, and reliability of the measures required. The Dupont film (Cd—Sn) density difference is a measure of the thermal neutron exposure and is independent of the presence of

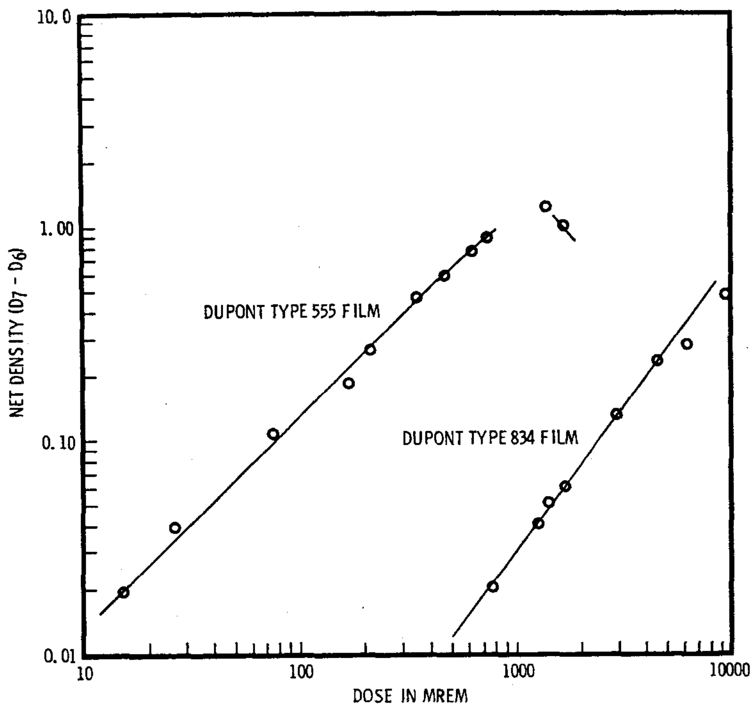

FIG. 7. Typical thermal neutron calibration curves for Dupont type 555 and type 834 films.

density (D_7), predict the expected OW density (OW_e) from appropriate curves, then use the ($OW—OW_e$) density difference to determine the B exposure; $(X + B)$—evaluate the X energy, and the X dose, predict OW_e due to the X dose, then evaluate B from the ($OW—OW_e$) density difference; (X only)—same as $(X + G)$ procedure, sum the apparent exposures; (G only)—under normal circumstances evaluate G by use of the OW, (D_1) or a thin filter density (D_3 or D_4); (B only)—evaluate the B exposure by use of the OW density.

other types of radiation in the exposure, that is: $(D_6 - D_5) = kN_{th}$, a result which follows from the fact that b_5 and b_6 are approximately zero and $g_5 = g_6$ by design. Although this measure is independent of the presence of the other types of radiation, the useful range of the measure is governed to some extent by the presence of other radiations. This dependence may be explained as follows: most thermal neutron calibration exposures and actual exposures are accompanied by a gamma exposure and as a result the net Cd and Sn density curves compose a pattern similar to a hysteresis curve. For such a pattern the density difference in question (Cd−Sn) maximizes at a certain density and continues to decline as the total exposure to the film is increased. Therefore, the use of the density difference must be governed by the gross density under the Cd filter if the possibility of ambiguous results is to be avoided. The gross density behind the Cd is dependent particularly upon the presence of radiations other than N_{th} and to some extent affects the useful range of the film for thermal neutron dosimetry. Figure 7 illustrates how this density maximizes for PuBe neutrons thermalized in paraffin. If a particular result has to be rejected because the gross Cd density is too high the data from a more insensitive film can be used to produce the desired result.

Fast neutron exposures are monitored with the Kodak film which are evaluated by the track counting technique. The track count is determined in the Cd filter area of the film by means of a projection microscope. A scanning technique is used to examine an area equivalent to at least 50 fields of view (6.125 mm^2). If this preliminary scan indicates that the film is exposed, enough individual fields are examined to produce a counting result with acceptable counting statistics ($\pm$ 20% at 95% confidence level). The required number of fields can be determined by use of the data gained from the first few fields counted. The dose is interpreted from an appropriate calibration curve. (It may be of passing interest that the average track production efficiency of PuBe neutrons in Kodak Type A film as determined by several observers with a microprojector using this technique is 6.0×10^{-4} tracks/nf.)

EMERGENCY MONITORING

The badge is presently equipped with a high range monitoring system (Tables 2 and 3) for neutrons which is patterned after the system used in the Hanford Badge.[7] This system extends the capabilities for evaluation of neutron exposures to cover the range which would be of concern should a serious radiation event occur. Although the present emergency system provides only for an extension of neutron monitoring capabilities, provisions are now being made to incorporate a high range gamma monitoring capability. It is anticipated that this system will consist of as many as three separate monitoring units, each containing at least 20 mg of Li-7 enriched LiF, and having a useful range of from 20 mr to 10^5 R. These units are to be contained in the reserve space in the top cavity of the dosimeter holder.

PERFORMANCE OF THE ROUTINE MONITORING SYSTEM

The routine monitoring performance of the badge described in this report has been investigated for a variety of exposures to X-rays, gamma-rays, beta particles, thermal neutrons, and various mixtures of these radiations, using the analysis techniques described earlier. The results of these analyses indicate that the routine monitoring performance of this system easily exceeds the applicable National Sanitation Foundation Film Badge Performance Control Limits.[11] A detailed description of the performance testing is not included in this report; however, the data is included in a separate report which can be obtained upon request from the authors.[12]

CONCLUSIONS

The film badge described in this report has been in service for over 18 months and has performed very satisfactorily. Although the badge is possibly the most extensive design in existence, analyses of the monitoring capabilities attainable with it in conjunction with the techniques and appropriate discretions presented in this report show that these capabilities easily meet and significantly exceed the performance requirements which have been set forth for film badge services.

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