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# ANALYSIS OF THE EFFECT OF HIGH ENERGY PROTONS ON ATM PHOTOGRAPHIC FILM

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# ANALYSIS OF THE EFFECT OF HIGH ENERGY PROTONS ON ATM PHOTOGRAPHIC FILM

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## I. INTRODUCTION

In discussing the effect of a proton energy spectrum on the photographic film to be carried on the ATM mission, it is necessary to determine experimentally a function which gives proper weight to the various proton energies. The following analysis provides a means of incorporating experimental data, obtained by exposing film to monoenergetic, monodirectional proton streams, into an analytical scheme which describes the effect on film of a proton energy distribution in space.

## II. ANALYSIS OF FILM DATA

The film density $d'$ is defined by the equation

$$d' = \log_{10}(1/T) \tag{1}$$

in terms of the fractional transmission T of a standard light ray. The net density d associated with some exposure Q is written as

$$d' - d_0 = d = d(Q) \tag{2}$$

where $d_0$ is an initial background density, and Q is the film exposure to radiation. In general, the dependence of d on Q, expressed as d(Q), and the Q associated with a given kind, energy, and amount of radiation will be determined experimentally.

It will be assumed for our purposes that exposures to various kinds and energies of radiations, simultaneously or in sequence, are strictly additive so that we can write

$$Q = \sum_i \sum_k Q_i(E_k), \tag{3}$$

where $E_k$ is the energy associated with the kind of particle identified by the subscript i. If there is a continuous distribution in energy of the particle population, Equation 3 may be written as

$$Q = \sum_i \int Q_i(E)dE = \sum_i Q_i \, . \qquad (4)$$

In discussing particle populations and film damage, it is convenient to define three functions. The particle differential energy spectrum $\phi(E,t)$ has units of particles/cm$^2$ sec MeV. We will neglect time dependence and write it as $\phi(E)$. We define the normalized differential energy spectrum as

$$\hat{\phi}(E) = \phi(E) / \int_E \phi(E)dE \qquad (5)$$

and the time integrated differential energy spectrum as

$$\Phi(E) = \int_0^T \phi(E,t)dt = T\phi(E) \, . \qquad (6)$$

From the experimental data, we can see that some particles are more effective than others in producing film darkening or increase in density, and we define the exposure associated with the radiation with energies between E and E + dE as

$$Q_i(E)dE = \Phi_i(E)F_i(E)dE, \qquad (7)$$

or

$$Q_i = \int \Phi_i(E)F_i(E)dE. \qquad (8)$$

The function $F_i(E)$ may be viewed as a measure of the effectiveness of particles of the $i^{th}$ kind in producing film darkening. In further discussions, the subscript i will be omitted and we will deal only with one kind of radiation, namely protons.

If one plots density d versus particles/cm$^2$, denoted by the symbol N, for several exposures to monoenergetic proton streams, curves such as shown in Figure 1 can be obtained. It appears reasonable and possible to map all these curves onto a single curve with the transformation,

$$Q(E_k) = F(E_k)N(E_k), \tag{9}$$

which is another way of saying that the increase of film density with exposure is independent of the kind or energy of radiation if we define the exposure $Q(E_k)$ properly. Note that Equations 8 and 9 are similar, except that Equation 8 is for a distribution in energy, and Equation 9 is for a monoenergetic stream such as is encountered experimentally in the determination of the effectiveness function $F(E_k)$.

If we draw a horizontal line at the level $d_m$ in Figure 1, we establish values for particle fluxes at different energies, which correspond to the same density $d_m$ and, by definition, to the same exposure $Q(d_m)$. We denote these flux values as $N(E_k, d_m)$, since they are numbers which depend on the particle energy $E_k$ and the film density $d_m$. From Equation 9, we can write

$$Q(d_m) = F(E_k)N(E_k, d_m), \tag{10}$$

or

$$F(E_k) = Q(d_m)/N(E_k, d_m). \tag{11}$$

Equation 11 states that $F(E_k)$ is a characteristic of a particle and its energy, although we may determine it by particular measurements

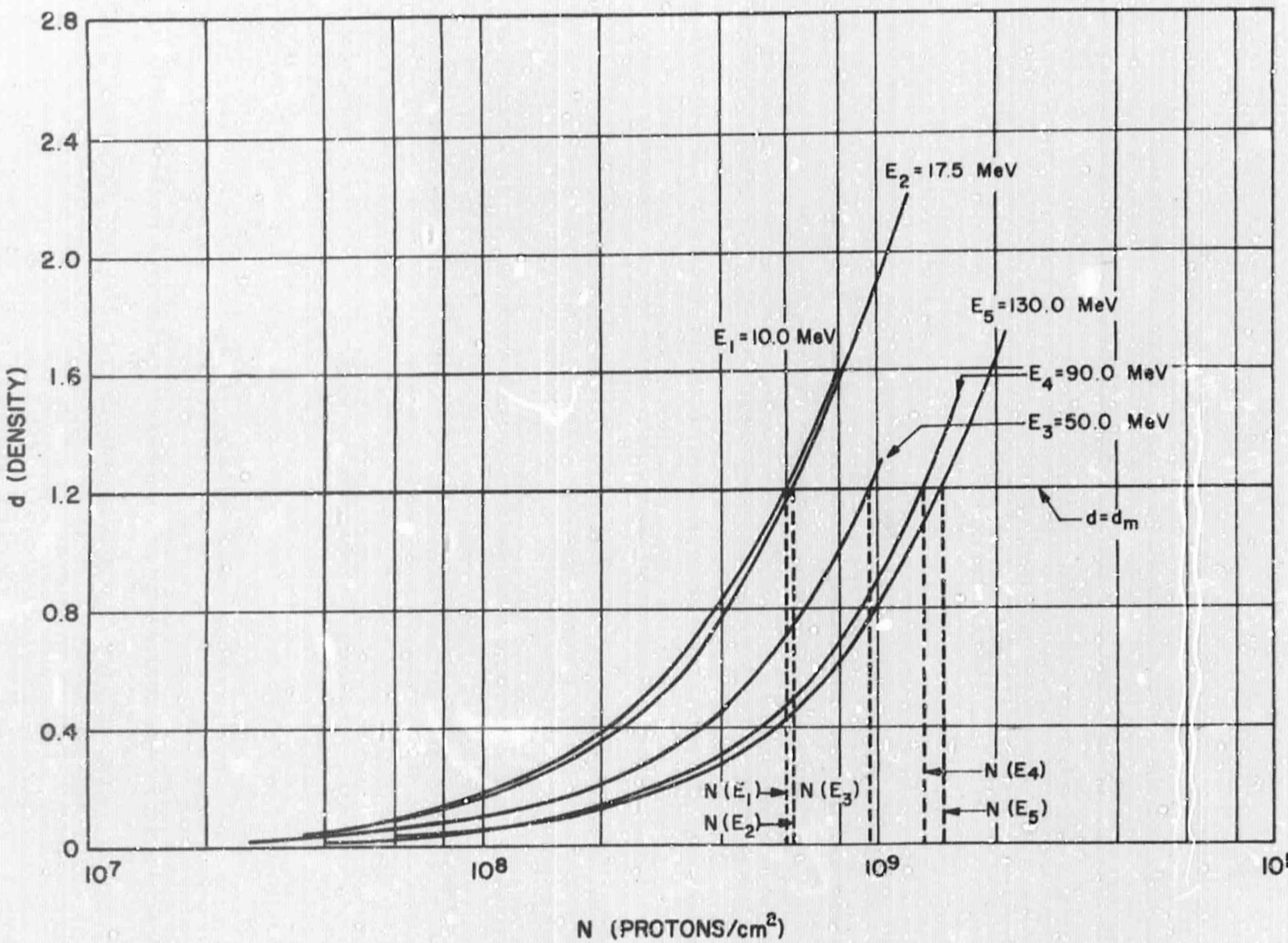


Figure 1. Density versus Proton Exposure for a Typical ATM film, with Proton Energy as a Parameter

of Q and N; accordingly, we remove the subscript k and write

$$F(E) = Q(d_m)/N(E, d_m). \tag{12}$$

Equation 12 contains the reasonable assertion that the effectiveness of a particle is inversely proportional to the number required to produce a given density $d_m$.

From Equations 7 and 11,

$$Q = \int \Phi(E)F(E)dE = \int \Phi(E)[Q(d_m)/N(E, d_m)]\,dE'. \tag{13}$$

Using the definition that

$$N\hat{\phi}(E) = \Phi(E), \tag{14}$$

we convert Equation 13 to

$$Q = N \langle Q(d_m)/N(E, d_m)\rangle, \tag{15}$$

where we define the average for any quantity y(E) as

$$\langle y \rangle = \int \hat{\phi}(E)y(E)dE. \tag{16}$$

In dealing with particle populations, we need to choose the units of Q such that we can easily obtain a plot of density versus time for a particular film. Accordingly, we define

$$Q = N, \tag{17}$$

the particles/cm$^2$ for the radiation exposure, so that we require

$$\langle Q(d_m)/N(E, d_m)\rangle = 1. \tag{18}$$

Since $Q(d_m)$ is a constant for our particular measurement

$$\langle Q(d_m)/N(E, d_m)\rangle = Q(d_m)\,\langle 1/N(E, d_m)\rangle = 1. \tag{19}$$

Therefore

$$Q(d_m) = 1/\langle 1/N(E, d_m)\rangle . \qquad (20)$$

Substituting Equation 20 into Equation 12 gives the following:

$$F(E) = \frac{1}{\langle 1/N(E, d_m)\rangle} \cdot \frac{1}{N(E, d_m)} \; . \qquad (21)$$

With this definition of $F(E)$, we return to Equation 9 and write

$$Q = F(E_k)N(E_k) \qquad (22)$$

as the change of variable which maps all the density versus $N(E_k)$ curves onto each other (i.e., equates each exposure to mono-energetic radiation, in terms of particles/cm$^2$, to an exposure to a spectrum $\phi(E)$ in terms of particles/cm$^2$).

To achieve the final result which we desire, namely a curve of film density versus time for a particular orbit and a particular film behind a specified shield, we proceed as follows:

a. Establish a normalized energy spectrum $\hat{\phi}(E)$ for the particular orbit and shield.

b. Establish a curve of $1/N(E, d_m)$ from curves of d versus $N(E_k)$, choosing a convenient value of $d_m$ as shown in Figure 1.

c. Compute $Q(d_m) = \langle 1/N(E, d_m)\rangle^{-1} = 1/\int [\hat{\phi}(E)/N(E, d_m)]\,dE$.

d. Compute curves of $F(E) = Q(d_m)/N(E, d_m)$.

e. Map each curve of d versus $N(E_k)$ onto a single curve of d versus $Q = N$ by the change of variable $Q = N = F(E_k)N(E_k)$.

f. Using $N = T\int\phi(E)dE$, plot curves of d versus T.

## CONCLUSION

The foregoing discussion has described an analytical scheme for incorporating experimental data, in the form of measured film darkening associated with monoenergetic, monodirectional proton streams, into a method of predicting the effects of the space proton spectrum on photographic film.