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Technical Memorandum

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A POSSIBLE METHOD FOR DETERMINING DISTRIBUTION OF FISSION FRAGMENTS IN THE CLOUD AND STEM OF A NUCLEAR EXPLOSION

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ABSTRACT

For prediction of fallout behavior, it is an aid to know how fission fragment activity is distributed in the cloud and stem of an atomic explosion. It may be possible to determine this distribution accurately and inexpensively by observing the luminous glow surrounding the cloud and stem and correlating it with the gamma-ray source distribution.

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A POSSIBLE METHOD FOR DETERMINING DISTRIBUTION OF FISSION FRAGMENTS IN THE CLOUD AND STEM OF A NUCLEAR EXPLOSION

1. Introduction

Current methods* of determining location of fission products in the cloud and stem of a nuclear explosion are expensive, and therefore the data few;[1, 2, 3, 4] but these data give some idea of how the activity is distributed among the various particle sizes.

Because of the limited amount of data various investigators have had to assume various activity locations in their models for computing fallout behavior. They have also exercised considerable freedom in choosing a distribution of this activity among the various particle sizes.[5] These two assumptions, naturally enough, are tailored so that the combined result matches observed fallout patterns.

For prediction of fallout behavior under new conditions, however, it would be an aid to know how the activity is distributed in the cloud and stem as a function of yield, burst height, and time after burst. The method proposed herein will, if successful, furnish this information inexpensively.

*Samplers or radiation-sensitive instruments carried by rockets, parachutes, and planes, including drones. Fallout collections also provide information on size and activity of particles.

Basically, the plan for determining this distribution is based on the tendency of air to become luminous when subjected to gamma-ray flux. This phenomenon occurs during a nuclear detonation and is especially intense during the last stages of fission process (Teller light).[6/] It is also visible on early morning shots where it appears to the naked eye as a purple glow of the air about the cloud and stem.[7-8/]

If we can determine the gamma-ray flux about the cloud and stem by observing this glow, we should be able to infer space distribution of these gamma-ray sources (fission fragments). By observing the air glow at various times we should be able further to follow the history of this distribution. Mathematical details of this distribution determination are covered in a later section; we are first concerned with the physical processes of the glow production which must be understood if we are to know the glow is a reliable index of gamma-ray flux.

2. Glow Production Processes

Only the Compton effect is important for the interaction of gamma rays from fission fragments (average energy 0.7 mev) with air. This interaction produces a fast electron which is knocked free of the parent atom and is decelerated by interactions with molecules of surrounding air. Some of these interactions only result in gain of molecular thermal energy at the expense of that of the electron, but others lead to ionization or excitation of molecules. It is the formation of these disturbed

molecules that is largely responsible for the glow radiation although a minor fraction (probably less than 1 per cent) results from the primary electron deceleration (bremsstrahlung). Excited molecules will return to the ground state, usually emitting a photon or series of photons to do so.* Ionized molecules follow a more devious history involving recombination with electrons, or more likely with other ions. The energy released on the recombination may appear as radiation, molecular heating, and/or disrupted bonds.

This bond description results in the formation of atomic nitrogen and oxygen as well as compounds of the two elements. These materials in their interactions lead to further light emission (afterglow).

With this cursory glance at the phenomenon, we may ask two questions: (a) Is the emitted radiation proportional to the gamma-ray flux? (b) How quickly after the gamma-ray interaction is the visible radiation released?

The answer to the first question seems obvious. Once the Compton electron is knocked from its parent, the processes of ionization and excitation it causes should be independent of the air density and nearly so of temperature since collision processes are atomic. However, the

*Teller light is observed to consist mostly of the second positive group of N_2 and N_2^+ bands.[6]

number of primary electrons produced by a given flux is proportional to the air density, so the amount of radiation emitted for a steady-state case should be proportional to the product of gamma-ray flux and air density.

The second question is not so easily answered. The excited molecules and ions return to the stable state quickly, usually in about 10^{-8} sec for an allowed transition. On the other hand, the recombination of ions is a much slower process because collisions are required. This recombination behavior is described by

$$\frac{dn}{dt} = -\alpha n^2 \tag{2.1}$$

where n is the number of ions of either charge per unit volume, t is time, and α is the recombination coefficient. For air α is sensitive to pressure and also shows a time dependence. For our purpose we may approximate with sufficient accuracy by using a value of 10^{-6} cm^{-3} sec^{-1}. Table 2.1 describes the behavior under various circumstances. It will be seen that the processes are sufficiently fast when compared with the cloud and stem development period (six or seven minutes).

The recombination of atoms to form molecules (afterglow) is an even more leisurely process. To estimate the response time, we turn to data obtained by Lord Rayleigh in a study of nitrogen afterglow.[9/] Assuming that a three-body collision is required for

recombination of atoms, we may extrapolate his results to atmospheric pressure, holding concentrations of active elements the same. It is then found that the intensity is down to one hundredth of the original in about 0.5 sec and to one ten thousandth of the original in 0.9 min. These again are fast compared to the duration of other cloud phenomena. However, this extrapolation is dangerous since reaction rates are sensitive to concentrations which, under field conditions, may well be much lower than those of Lord Rayleigh's experiment.

More detailed data are provided by a report by A. L. Gardner along with a summary of research on nitrogen afterglow.[10] From this work, one may infer that rates are probably far too low for the reaction of atomic nitrogen and nitrous oxide to be significant under the irradiations listed in Table 2.1. Again, this extrapolation is somewhat dangerous since other reactions may produce afterglow, and air carried along with the fireball may have received high irradiations and have larger amounts of atomic nitrogen as well as nitrous oxide. It would seem some experimentation is in order to duplicate shot conditions more closely.

Aside from these mechanisms there are other glow production processes involving the recombination of electrons and positive ions. These are not important here since electrons are easily captured by neutral oxygen molecules.

TABLE 2. 1

Examination of Time Response
of Air Ions Recombination Process (STP)

Situation	Response	Relation
* Irradiation of 3. 5 roentgens/sec, after t = 0	Glow 80% of final brilliance in 0. 018 sec, 90% of final brilliance in 0. 022 sec	The ratio of brilliance to final is equal to $(\tanh(83.6t))^2$ where t is time in seconds
Steady irradiation with 3. 5 roentgens/sec, cut off at t = 0	10% of initial brilliance in 0. 026 sec	Ratio of brilliance to initial is equal to $\frac{1}{(1+83.6t)^2}$
† Irradiation of 0. 035 roentgens/sec, after t = 0	Glow 80% of final brilliance in 0. 18 sec, 90% of final in 0. 22 sec	Ratio of brilliance to final is equal to $(\tanh(8.36t))^2$
Steady irradiation of 0. 035 roentgens/sec, cut off at t = 0	Glow 10% of initial brilliance in 0. 26 sec	Ratio of brilliance to initial is equal to $\frac{1}{(1+8.36t)^2}$

*This radiation level was chosen as that to be expected 1000 feet from the cloud or stem at 1 minute after burst; it is probably lower than actual.

† This radiation level was chosen as that to be expected 1000 feet from the cloud or stem 5 minutes after burst. Levels of this sort have actually been observed at this time.[11]

It seems probable that energy is released as radiation sufficiently soon after the first interaction so that we may assume that the light emitted is proportional to the product of instantaneous gamma-ray flux and air density. The role of the slowest process, atomic recombination, must be checked further.

3. Theory of Measurement

It is evident that to determine the distribution of the fission products in the cloud and stem we will somehow need to measure the intensity of the gamma-ray flux at particular points or in some way correlate it with observed glow. At first this seems a difficult task since the glow is a volume phenomenon; and looking at the glow along a line-of-sight, one sees the contributions of the entire volume along with background.

One then realizes, at first intuitively, that change of intensity as one moves the line-of-sight closer to the gamma-ray source should be proportional in some manner to the intensity at the point nearest the source on the line of sight. Such a technique has the advantage of eliminating background.

Before exploring this possibility analytically, the physical nature of this line-of-sight must first be considered as well as the contribution of a volume radiator to it. To be more explicit, let us consider a camera with the plate situated at the focal distance (focused for distant objects). A small area on the film then represents contributions from

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volume emitters in a cone whose apex is situated at the camera. Furthermore, for a photon to register on the plate it must first pass through the lens. The result of this is that the contribution to this plate area from a thin element centered on and perpendicular to line-of-sight of a volume source is independent of the separation of camera and element, providing the element subtends the cone. This feature is used in our analysis; similar arguments can be made for other optical systems.

Analytical calculations may be facilitated by reference to Fig. 3. 1. The contribution (C) of the volume along the line-of-sight may be computed by the integral:

$$C = 2K\int_0^\infty I\left((x_o^2 + y^2)^{1/2}\right) dy \qquad (3.1)$$

where K is a suitable constant involving the product of air density and a conversion efficiency, I is the intensity and a function of the radius $(x_o^2 + y^2)^{1/2}$ as shown, while the meaning of x_o and y is evident from the diagram. The example is worked out for a point source; we will later generalize the result to a distributed source.

We may examine the variation of C with x_o by differentiating; the result is:

$$\frac{\partial C}{\partial x_o} = 2K_1\int_0^\infty \frac{\partial I\left((x_o^2 + y^2)^{1/2}\right)}{\partial x_o} dy \ . \qquad (3.2)$$

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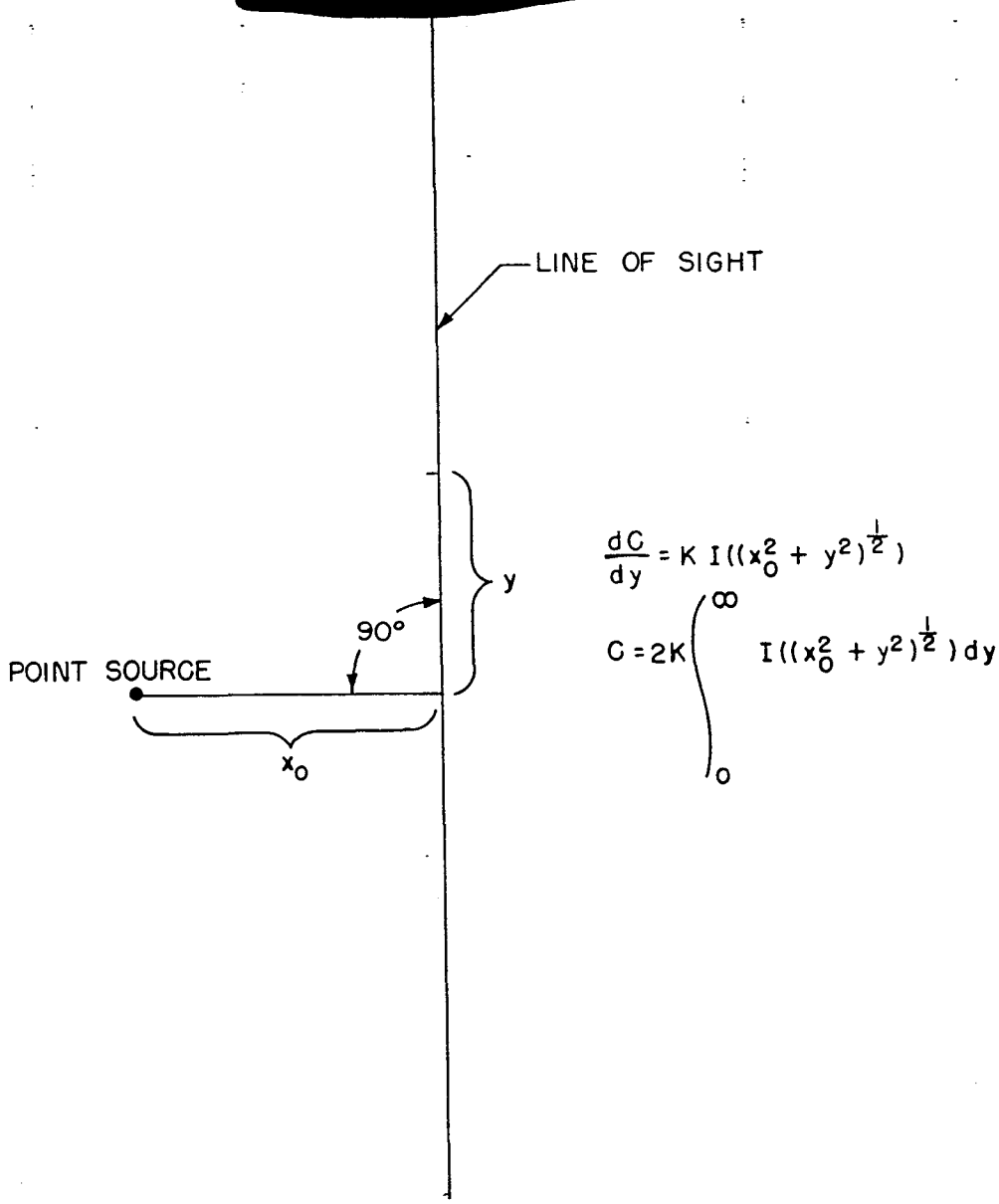

Fig. 3.1 Illustration of integral (3.1)

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If it is assumed that intensity is an inverse power of radius, $\left((x_o^2 + y^2)^{1/2}\right)^{-n}$, then it is found that $\frac{\partial C}{\partial x_o}$ is indeed proportional to $I(x_o)$,* i.e., I at y = 0. Unfortunately such an intensity description is not applicable; instead, the situation is:

$$I\left((x_o^2 + y^2)^{1/2}\right) = \frac{K_1}{x_o^2 + y^2} e^{-\frac{(x_o^2 + y^2)^{1/2}}{\lambda}} \qquad (3.3)$$

where λ is mean free path. Using this expression, Eq 3.2 is not directly integrable, but may easily be evaluated by numerical methods. The results are displayed in Fig. 3.2 where the ratio of $\frac{\partial C}{\partial x_o}$ $2K_1$ $I(x_o)$ is plotted as a function $\frac{x_o}{\lambda}$. This ratio is a slowly varying function of $\frac{x_o}{\lambda}$ between the values of 0.5 and 4. To give an idea of the range of applicability of this curve, λ is about 10^3 ft.

One is tempted, if possible, to simplify by ignoring variation of this ratio. To see whether this is possible, a numerical check was made using the array of point sources displayed in Fig. 3.3. Unfortunately, errors as much as 12 per cent arise unless one restricts sampling points severely. Thus it seems necessary to incorporate the curve of Fig. 3.2 in our analysis.

Having examined the point source approach we may consider a distributed source. From the optical situation and the point analysis,

*The line-of-sight contribution (C) may also be correlated with $I(x_o)$ for this case since $C/x_o I(x_o)$ is independent of x_o.

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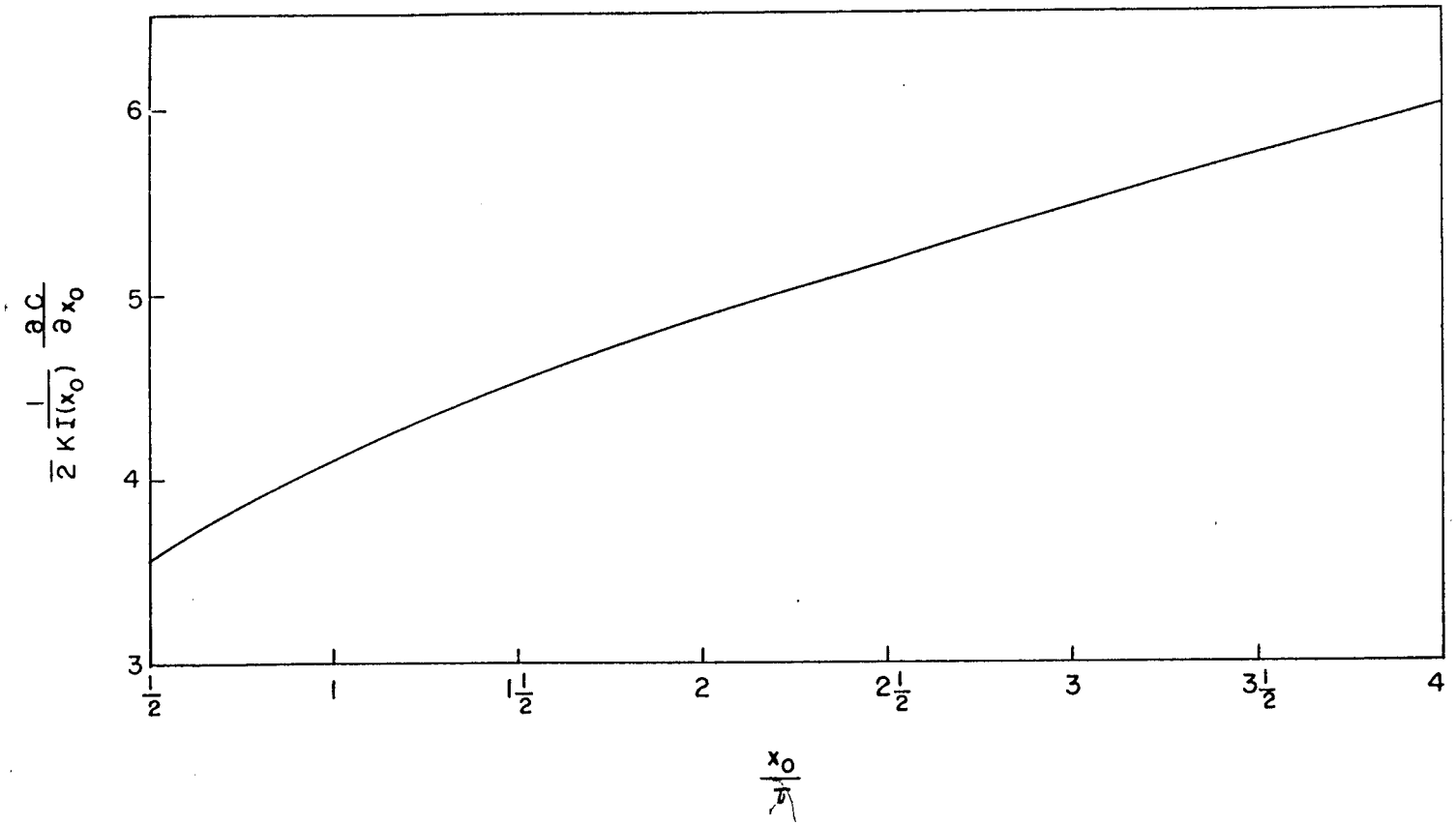

Fig. 3.2 Plot showing variation of $-\frac{1}{2KI(x_o)} \frac{\partial C}{\partial x_o}$ with $\frac{x_o}{\lambda}$ for a point source having an attenuation law with radius of $I \propto \frac{1}{(x_o^2 + y^2)} e^{-\frac{(x_o^2 + y^2)^{1/2}}{\lambda}}$

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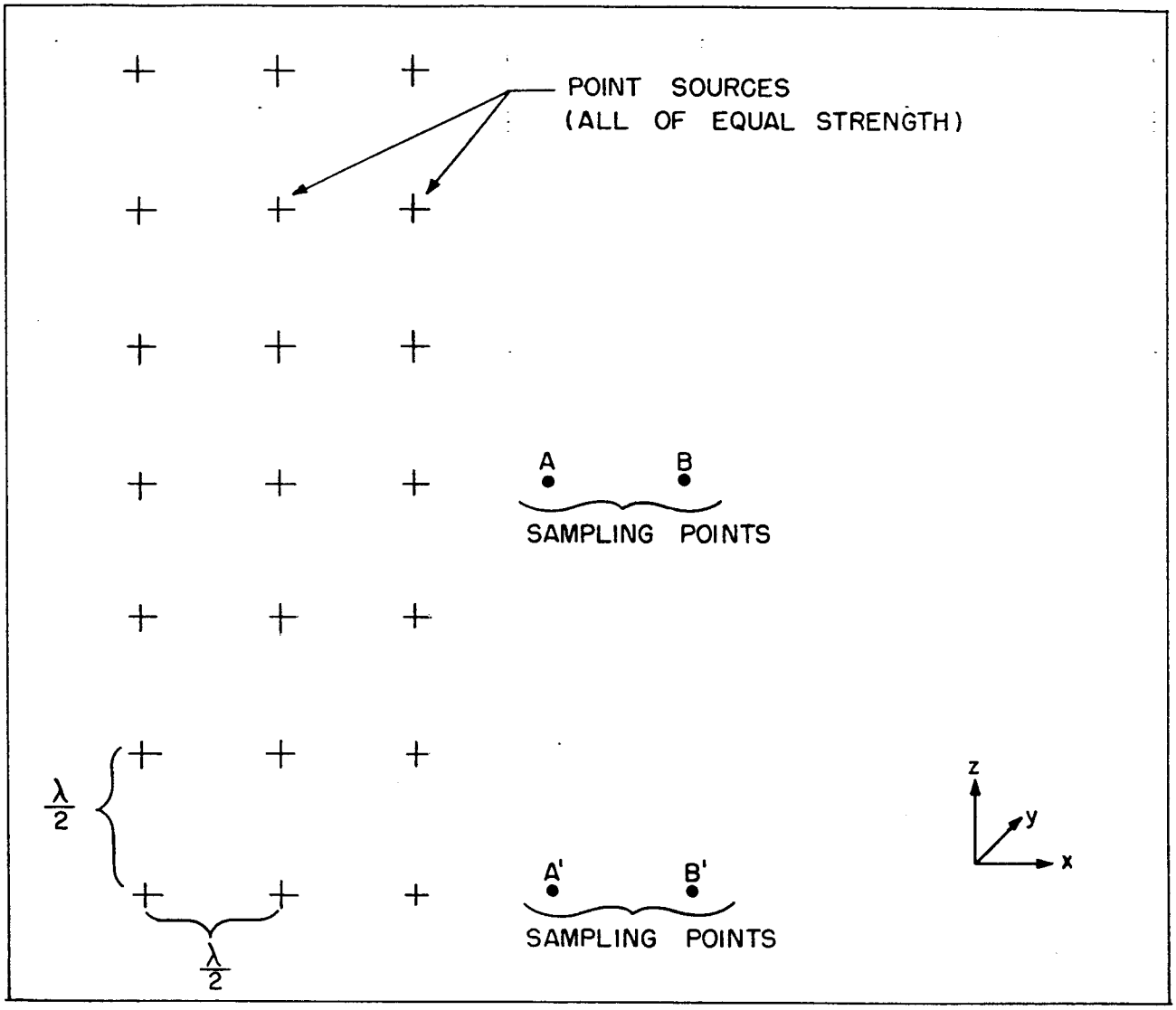

Fig. 3.3 Array of point sources used for checking errors incurred in neglecting variation of the ratio of $\frac{\partial C}{\partial x} / I(x_o)$ with x_o/λ

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it became evident that it was simpler to examine the direct contributions of elements of the distributed source to the line-of-sight rather than attempt correlation of the point with maximum gamma-ray flux brought about by the total distributed source cone. This aspect is also treated further in the section Analysis Technique. For the present we may say that since the contribution of an extended source to a line-of-sight is independent of the distance between the source and the receiver, Eq 3.2 can be used directly for an extended source, considering each element of the source as a point.

From a practical standpoint it is convenient that we do not actually need to move the line-of-sight sidewise to study the glow intensity gradient. Since the cloud and stem cross section is circular, rotation of the line-of-sight from the viewing point is equivalent to sidewise translation. This equivalence will prove useful in analysis of data obtained by the method proposed in the next section.

From these considerations it is evident that we will not measure the gamma-ray intensity at a point as we originally set out to do. However, we will be able to measure approximately the contributions to a line-of-sight of the distribution. As it turns out, this is just as satisfactory for determining the distribution; in fact, it simplifies the computational procedure.

4. Experimental Procedure

The experimental technique proposed herein is a simple one; and if more precise results are required than are anticipated, refinements of technique are obvious. However, for a first trial it seems worthwhile simply to photograph the glow at intervals and to examine the distribution of the glow. Then densitometric measurements may be performed to determine the change of glow intensity with radius. These photographs may be either in color or in black and white. If black and white film is used it might be worthwhile to employ a filter to reduce background.

It is in the experimental results that limitations of the technique are apt to appear. Photographs of late stages of the glow have not been obtained, and it may prove impossible to obtain them. Photographs of the early stages have been obtained by the LASL Graphic Arts Group with color film. However, the film was exposed for several seconds during the rapid rise of the early cloud and is probably too smeared for reliable analysis.

why not?

It will be seen that much depends on photographic results; not only the possible limitations discussed above, but also the method employed in analysis. We have, for example, assumed that backgroud illumination will be sufficient so that the gradient of glow intensity (Eq 3. 2) is more reliable than direct intensity measurement (Eq 3. 1). This concern may be proved unnecessary; if so, the analysis technique discussed in the next section would be altered to this new circumstance.

In turn, to develop proper photographic techniques requires some trial and error to optimize results. One has a considerable variety of exposures, films, filters, etc., to choose from, and it may be worthwhile to narrow the possibilities on the next operation with a few trials.

The negatives obtained should be a useful form of data. We have intensities and the cloud size, location, and other dimensions available at once. One must have a standard set of intensities put on the same film before processing which will enable determination of the film properties necessary for intensity measurement. Fortunately, relative intensities are all that are required so one does not have too much trouble with this condition. With this procedure the error should be about five per cent.

5. Analysis Technique

In the previous sections we have described the techniques of determining contributions of a distributed source to a line-of-sight. We are now ready to apply measurements of the gradient of intensities perpendicular to lines-of-sight to determine source distribution. The product of these observed intensities with air density (lines-of-sight are approximately horizontal if the camera is sufficiently distant) is proportional to the gamma-ray flux on the line-of-sight. We then infer the distribution that accounts for this observed flux pattern. To do this we invoke a number of assumptions to simplify analysis. These are:

1. Activity is confined to the visible cloud. This assumption seems reasonable since bomb debris is mixed with earth drawn up by the burst; or for a high burst, debris is visible along with the products of bomb action on air and water vapor.

2. Activity is uniformly distributed throughout the visible cloud or stem at a given elevation. This assumption is less justified, but is convenient and as well justified as another arbitrary distribution. (That assumption 1 and 2 are reasonably well justified may be verified by examining WT-11.[1/])

3. The attenuation factor $\frac{1}{\lambda}$ is the same at a given elevation in the cloud or stem as in air at the same elevation. This assumption is justified in the later stages as the cloud stabilizes, but it overestimates the attenuation factor in early stages. If greater precision is required, we may achieve it by examining cloud rate of rise and allowing for the difference in density in our computations.[11/] At this stage such an elaboration seems unrealistic.

4. The character of the gamma-ray is not a function of time or distribution, i. e., if fractionation occurs it does not profoundly affect the effective distribution.

In principle, if we explore the distribution of glow intensity with enough detail, we might ascertain completely the relative distribution within the cloud and stem by use of the integral

$$\left| \frac{\partial C}{\partial l} (x_o, z_o) \right| \alpha \int_V \frac{\rho_v(z)\, dv}{\left((x - x_o)^2 + (z - z_o)^2\right)} \; e^{-\frac{\left((x - x_o)^2 + (z - z_o)^2\right)^{1/2}}{\bar{\lambda}(z, z_o)}}$$

$$f\left[\frac{\left((x - x_o)^2 + (z - z_o)^2\right)^{1/2}}{\bar{\lambda}(z, z_o)}\right] \cos \Theta \qquad (5.1)$$

Here $\frac{\partial C}{\partial 1}(x_o, z_o)$ is the glow gradient, corrected by multiplying by air density, which is obtained by sighting near the point $x = x_o$ and $z = z_o$. The integral is carried over the cloud and stem volume; $\rho_v(z)$ is the source strength per unit volume, dv is volume element, and $\frac{1}{\bar{\lambda}(z, z_o)}$ is the mean value of the attenuation factor between z and z_o.* The expression,

$$f\left[\frac{\left((x - x_o)^2 + (z - z_o)^2\right)^{1/2}}{\bar{\lambda}(z, z_o)}\right]$$

is a sensitivity factor described by the curve on Fig. 3.2 †, while Θ is the angle between the direction the gradient is taken and the direction to the element.

*Defined by ---------- $\frac{1}{\bar{\lambda}} = \int_{z_o}^{z} \frac{1}{\lambda}\, dz \Big/ (z - z_o)$

† $\left(\frac{x_o}{\lambda} \text{ corresponds to } \frac{\left((x - x_o)^2 + (z - z_o)^2\right)^{1/2}}{\bar{\lambda}(z, z_o)} \right)$

In practice such a procedure is far too laborious to be justified; we simplify by slicing the cloud and stem in horizontal sections and assume that $\rho_v(z)$ is constant throughout each section. Then by taking as many lines-of-sight (appropriately spaced) as we have sections we may compute the values of ρ_v which explain the observed glow distribution. As a check, a few other lines-of-sight might then be included in the computation to see that reasonable consistency is obtained.

One performs the numerical integration of Eq 5.1 for each line-of-sight. These give a set of weight factors (A) for the ρ_v for each sector, and one obtains the relation

$$\left| \frac{\partial C}{\partial \ell} (x_{oi}, z_{oi}) \right| \alpha \sum_{j=1}^{n} A_{ij} \rho_j \quad , \tag{5.2}$$

where n is the number of segments chosen. The process is repeated for next line of sight, giving an analogous relation. After completing the procedure for each observation point, one may solve for the relative values of $\rho_1 - - - \rho_n$. The procedure is not quite as formidable as it sounds since factors A_{ij} decrease rapidly with distance and may soon be ignored. This simplifies both integration and solution of the linear equations. As a feasibility check, we have carried out numerical integrations on a similar problem, that of obtaining the flux at a point from a cylinder containing uniform source distribution. The relative contribution as a function of the height, z, is displayed in Fig. 5.1. This curve was easily obtained, requiring only about two hours.

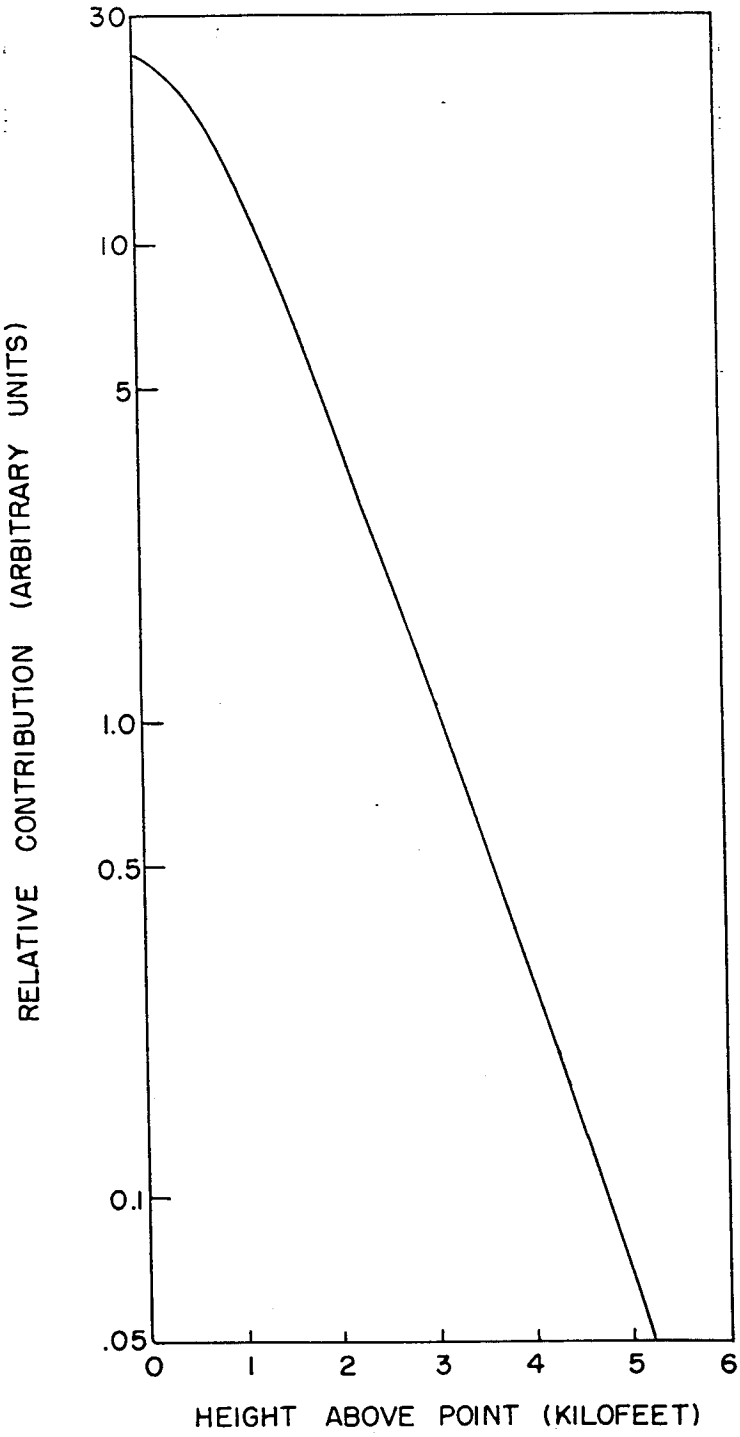

Fig. 5.1 Relative contributions per unit height to gamma-ray flux at a point 1000 feet from edge of a cyclinder 2000 feet in diameter filled with a uniform source (λ assumed to be 1000 feet)

6. Summary

The preceding discussions are part of the results of a feasibility study to determine whether it is possible to locate fission fragment activity by utilizing the purple glow induced in air by gamma rays from these fragments. On the whole, results are encouraging, more so than one would imagine on first examining the possibility. However, there remain troubling questions, namely the significance (if any) of atomic recombination in glow persistence and whether we may obtain usable photographs in the late cloud stages. The former question may probably be cleared up by a further search of the literature and/or research; the second can be answered only by trying.

If the technique proves successful, it should be a useful tool for it can, at little expense, provide information of fission product activity distribution in the cloud and stem as a function of yield, burst height, and time.

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