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LOW LEVEL RADIATION ALTIMETER SYSTEM STUDY

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ABSTRACT

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Several nuclear radiation techniques have been studied as possible means for altitude measurement above the lunar surface, for the range of 0 to 50 ft. Both direct (sources ejected and located on the surface during measurement) and indirect (source aboard the vehicle) systems were considered.

Indirect systems may use charged particle primary radiation (electron beams, alpha and beta particles), neutral particle beams (neutrons), or electromagnetic (x and gamma rays) radiation. Return radiation from the surface is measured. Indirect charged particle systems were rejected because of attenuation effects in the rocket exhaust gas, while neutron systems were rejected because of the large amount of hardware required. A gamma backscatter system, using photons of moderate energy (60 kev) was found to be very promising since the source strength requirement ($\sim$12 curies) is practical and the weight of the source and detector could be small ($\sim$5 lbs.). The altitude indication would be dependent on lunar surface composition (possibly with an uncertainty of ±25%) if altitude is based solely on detector response. However, if information from another altimeter system (as from the radar altimeter at say 50 ft.) is used, composition dependence can be avoided as the appropriate scale factor would be provided at a known starting altitude. It appears feasible, therefore, to make a gamma backscatter system that will be independent of lunar composition and accurate enough to meet the specifications provided by MSC.

Author

Gamma sources were also considered for direct systems. It was found that the direct gamma system requires more source strength than the gamma backscatter system, and considerably more hardware.

It has been concluded that the gamma backscatter system is the best selection, and that prospects of successful application are promising. A further program of research and development has accordingly been recommended.

I. Introduction

The purpose of this study was to determine the feasibility of utilizing radioisotope and nuclear radiation techniques for low level altitude determination during a lunar landing. Two systems were suggested by MSC as possible approaches: a directional detector system in which the direction and distance of several jettisoned radioactive sources relative to the vehicle were used to compute altitude, and a gamma backscatter system in which both source and detector are located on the vehicle and the scattered radiation due to the proximity to the landing surface is used to measure altitude. The first system may be termed as "direct" in that direct radiation from the source is utilized, while the second method correspondingly may be referred to as "indirect" since the measured radiation comes from interaction with the lunar surface.

Both direct and indirect systems have been studied, and radioactive sources as well as electrical generation systems were considered. It was the constant purpose of the study to eliminate as quickly as possible (of course on technically justifiable grounds) systems which would have great difficulty in succeeding, or which were obviously at a decided disadvantage compared to other candidates. In this way it was hoped to make more real progress on workable ideas.

With this in mind, it will be seen that the largest effort was devoted to gamma backscatter and direct gamma systems; and further that once the latter was shown to have no advantages, a detailed look at the associated hardware for this system was not attempted. The time was rather spent in delineating as far as possible the likely physical form of the gamma backscatter system.

Liberty was taken to simplify the suggested direct system before analysis, so that the most favorable form of such a device could be examined. It was shown, for example, that the angular locator system is actually unnecessary. This would not only make the system more practical in terms of hardware and reliability, but incidently simplified the approach to the analysis as well. While this system appears less suitable than the backscatter system, it is believed that our triangulation analysis and postulated principle of operation represents a unique and novel approach to the problem.

The obvious objection to the backscatter approach, that of lunar surface composition dependence, probably can be quite successfully avoided by use of a ratio technique. Thus, altitude is determined from the ratio of counting rate at any altitude to the counting rate at a known starting altitude (say 50 ft.). It is shown that the composition dependent terms will cancel out. This solution should not be objectionable since it is understood that a low altitude radar system will be aboard anyway; and its inherent accuracy of $\pm$ 1 ft. at 50 ft. has been included in the error analysis.

The scattering formulation mentioned above is of the single scattering type and is basic. There is no doubt about its correctness since all the principles are well known. Single scattering experiments performed by the authors* in the past have given excellent agreement between theoretical and observed values of "reflection" coefficients for a wide variety of target materials. It is emphasized that this analysis, and the experimental work mentioned above deal solely with single scattering, whereas in fact some multiple scatter by the surface will occur. This contribution will be much smaller, and it is believed that even the multiple scatter component will manifest at least a first order cancellation of composition dependence. This must be shown by a very carefully executed experimental program, mentioned in the Section VI, Recommendations. It would require too large an effort to have been included in the present work, for it deals with the exact description of a small effect. It is obviously important, however, that this step be taken. All other principles considered in this work are well known so that basic experimental verification is unnecessary. The next effort, if such is to be pursued, must by contrast include considerable experimental work.

Statistical, time constant, and radiation background analysis are vital to the measurement of any time varying phenomena by radiation means. These factors have therefore been given appropriate emphasis in the context of the present application.

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* Report on The Measurement of X-Ray Scattering Coefficients for Selected Primary Energies and Target Materials, by L. Bird, J. McCue, and C. Ziegler, Tracerlab Technical Report, December 22, 1959.

At least three areas of information required for this study are very sketchy: lunar surface composition, dust conditions, and radiation background. It is no doubt true that these factors will be clarified considerably as the result of future unmanned lunar probe research. As this information becomes available it will be very useful in carrying out further work on this device. One would expect that all factors of significance to the operation of a nuclear radiation altimeter will be known in adequate time to properly design such a device for manned spacecraft use.

It has been found that the gamma backscatter system shows considerable promise, and a further program of work has, therefore, been recommended.

II. Indirect Systems

A. General Considerations

Indirect systems by definition employ the principle of measuring return radiation from the object whose location is to be found - in this case the lunar surface. The detected radiation may be a scattered "version" of the primary radiation, or it may be different in kind. For example, electrons can cause x-ray production at the target and these x-rays might be detected.

A first step in weeding out potential candidate systems is to estimate the attenuation in the rocket exhaust cloud. This cloud will always be present since the rocket is expected to be on until contact with the surface. Thus, if the exhaust interferes with proper altimeter operation, the candidate system may be rejected at once. In this way it is possible to quickly restrict the field of study. This approach has been pursued so that the most promising approach could be examined in greater detail.

By the same philosophy, little time was devoted to the "machinery" of electrical generator systems when it became clear that small volume radioactive sources of reasonable strength could be used. To do otherwise would have meant a dilution of the effort on the most promising approach.

Some consideration of the possible effect of a dust cloud was given in the context of the gamma backscatter system, even though MSC representatives do not currently think such a cloud will exist. This early work may be useful if further data on the cloud becomes available at a latter date.

B. Attenuation In The Gas Exhaust Cloud

It must be the case for any scattering system that the attenuation by the exhaust cloud, going down to the surface and back again, is negligibly small. Data was provided by MSC concerning the exhaust gas pressure and temperature at various area ratios. These ratios are the ratios of the cross sectional area of the exhaust cloud to the cross sectional area of the top end of the nozzle. Average molecular weight was also provided. It was assumed that the shape of the exhaust gas cloud is given by the extension of the sides of the conically shaped nozzle as shown in

Figure 1. Using this assumption the distances from the nozzle corresponding to the designated area ratios were calculated, and using the ideal gas law the density associated with each distance was determined. The density-distance profile thus derived is also indicated in Figure 1. For purposes of calculation this profile was fitted with an exponential function, (note the dashed line) the result being $\rho(x) = 2.5 \times 10^{-6} \exp(-.278\ x)$ grams/cm^3 where x is the distance in feet from the end of the nozzle. The two-way radiation transmission T through this cloud is at least $T = \exp\left[-60.96\,\alpha \int_0^h \rho(x)\,dx\right]$ where α is the mass absorption coefficient for the radiation being used in units of cm^2/gram and h is the altitude in feet. The worst case is for h = 50 ft. Integration for this h gives $T = \exp\left[-5.5 \times 10^{-4}\alpha\right]$. Values of α and T are tabulated below for various radiation sources.

Source	Radiation Type	Energy	α (cm^2/gram)	T
Pm-147	beta	E_m = 123 kev	370	.815
Sr-90 } *	beta	E_m = 610 kev	60	.977
Y-90		E_m = 2.2 mev	14	.992
Am-241	gamma	E = 60 kev	.183	.99990

* in secular equilibrium

It is evident that for a backscatter system a soft beta emitter like Pm-147 would not be suitable due to attenuation in the exhaust gas. The backscatter signal would depend upon exhaust gas density as well as altitude. Even with an energetic beta source such as Sr-Y-90 the effect is still not clearly negligible. Further, if a dust cloud were present (caused by exhaust gas striking the lunar surface) additional attenuation would occur and this would be objectionable. Therefore, a beta backscatter system is probably not a safe choice. By the same token an alpha particle backscattering system can be eliminated since absorption coefficients are generally greater than for beta particles.

It is furthermore clear that a system in which electrons are generated electrically and directed to the surface, where they may be scattered and may also produce bremsstrahlung x-ray photons (either of which could be detected at the vehicle) would require electron energies of several Mev to be certain that unwanted attenuation effects are avoided. The hardware required for such a generator would greatly exceed the volume and weight needed for a gamma backscatter system. Therefore, these types of indirect systems are not considered further, and we shall concentrate on the gamma backscatter approach.

C. Geometry of Backscatter Configuration

The essential features of the backscatter geometry may be derived by considering a point source, and a detector located very near to it (but shielded from it). This development is independent of the radiation type since it deals purely with geometry. Consider a differential area dA at the scattering surface defined as in Figure 2. The area of the circular ribbon is

$$dA = 2\pi r^2 \sin\theta d\theta$$

The fraction f of the emanations which leave the source and are impingent on dA is $dA/4\pi r^2$, since $4\pi r^2$ represents the surface area of a complete sphere with the source at its center. Thus,

$$f = \frac{1}{2} \sin\theta d\theta$$

If the probability per unit solid angle of backscatter is denoted by γ, and since the detector subtends a solid angle $\omega = \pi R^2/r^2$* where R is the detector radius, the counting rate due to scattering from dA is

$$dS = \frac{\pi}{2} \gamma q \left(\frac{R}{r}\right)^2 \sin\theta d\theta \qquad (1)$$

where q is the emanation rate of the source. r is related to h and θ by $r = h/\cos\theta$. Hence, Eq. (1) may be rewritten

$$dS = \frac{\pi}{2} \gamma q \left(\frac{R}{h}\right)^2 \cos^2\theta \sin\theta d\theta$$

Integration over the whole range of θ from 0 to θ_{max} gives the counting rate due to the entire irradiation surface. The result is

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* This applies for $r \geq 3R$. This condition is satisfied even for the vehicle after landing since both source and detector would have to be mounted above the plane of the landing surface for protection against damage due to possible surface irregularities. A typical detector might have a radius R of 3 in. or less so that the corresponding r for which the value of ω given above applies is 9 in. or more. It is likely that both source and detector would be mounted at an even greater distance above the plane defined by the landing pads, so that the ω above is entirely adequate.

$$S = \frac{\pi}{6} \gamma q \left(\frac{R}{h}\right)^2 \left[1 - \cos^3\theta_{max}\right] \quad (2)$$

It is to be noted that the basic dependence on altitude is simple inverse square. This is because of the fact that the number of emanations impingent on the surface is a constant independent of altitude, viz., all the emanations in the angular range of $2\theta_{max}$ defined by the source collimation. The area being irradiated changes, of course, but not the total rate of incidence on this area. This area then acts as a constant source (though distributed) of secondary radiation producing the usual inverse square geometry dependence.

It has been assumed that the detector has a wide field of vision so that collimation at the detector is such that none of the irradiated area is obscured.

The detector response increases with increasing irradiation half angle. A plot of $1 - \cos^3\theta_{max}$ vs. θ_{max} is shown in Figure 3 and indicates the value of using a relatively large field of irradiation. Little improvement is, however, effected by use of irradiation half angles larger than 70°.

It is of interest to note that the response per unit of surface area is greatest at the center of the irradiated area and diminishes for points off center. The fall off can be large at the outer periphery of the irradiated area for large values of θ_{max}. The radius of the circle of irradiation is obviously $r_{max} = h \tan\theta_{max}$, but since all parts of this circular area do not contribute equally to the detector response, an effective circle of radiation with radius $r_{eff} < r_{max}$ may be defined which will serve as an index of the size of the area upon which altitude information is based. Let a hypothetical circle on the surface be defined such that if the radiation flux incident upon it were uniform, and if all parts of this area are considered to be the same distance h from the detector, then the response would be identical to that obtained in the real case. For this hypothetical irradiation field response per unit area is uniform, thus

$$S_{eff} = \frac{Q(\pi r_{eff}^2)\gamma}{(4\pi h^2)} \left(\frac{\pi R^2}{h^2} \right)$$

and this is to be equated to S [Eq. (2)]. When this is done, the resulting equation may be solved for r_{eff}. This gives

$$r_{eff} = h \left[\frac{2}{3} (1 - \cos^3 \theta_{max}) \right]^{1/2}$$

A plot of r_{eff}/h is shown as a function of θ_{max} in Figure 4. For large irradiation half angles ($\theta_{max} \to 90^{\circ}$), r_{eff} approaches 0.816 h.

This type of geometry is advantageous in several respects. First, the required source strength will be much less than any scattering system in which triangulation is used to determine altitude, rather than gross response, since such systems require a high degree of both source and detector collimation and since these systems must incorporate "searching" (source or detector motion) which utilizes a major part of the available measurement time. At the higher altitude end of the intended range of operation a large area (large r_{eff}) contributes to the altitude measurement, thus giving a better average than could be obtained with a system based on computation of average altitude from a few particular points on the surface. At low altitude r_{eff} is small, suggesting the use of a few source-detector pairs, perhaps one pair associated with each landing pad. In this way precise information concerning landing conditions might be available.

D. Derivation of Reflection Coefficient for X and Gamma Rays

For large scattering angles (backscatter) the principle type of scattering will be due to Compton interactions in which primary photons are scattered by the atomic electrons of the "target" atoms. The primary photon energy is shared by the scattered photon and the recoil electron. The energy of the scattered photon is given by

$$E' = \frac{E}{1 + \frac{E}{m_o c^2}(1 - \cos\theta)} \tag{3}$$

where E is the primary photon energy, $m_c c^2$ is the energy equivalent of the electron mass (511 kev) and θ is the scattering angle. The differential cross section for Compton interaction is given by the well known Klein-Nishina formula

$$\frac{d\sigma}{d\omega} = 3.92 \times 10^{-26}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'} + \frac{E'}{E} - \sin^2\theta\right) \tag{4}$$

(cm^2, steradian^{-1}, electron^{-1})

The probability of scattering in the direction θ per unit solid angle in this direction, per unit of path length traversed in a medium is given by

$$\frac{dP}{dx} = \frac{d\sigma}{d\omega} N_o \rho \sum \frac{\Psi_i Z_i}{A_i} \qquad (5)$$

where N_o is Avagadros number (6.025×10^{23}), ρ is the mass density (grams/cm^3), Z_i is the atomic number of the i^{th} type of atom in the medium, A_i is the associated atomic weight, Ψ_i is the fraction by weight comprised by the i^{th} type element, and where the summation is taken over all the elements of the medium. It will be recognized that $N_o \rho \sum (\Psi_i Z_i/A_i)$ represents the number of atomic electrons per unit volume of the medium.

This result may be applied to the problem of determining the scattering probability, or "reflection" coefficient for a plane surface of large thickness as follows. See Figure 5. Let an x or γ ray photon impinge on the surface at an angle ϕ, to the normal of the surface. The probability that it will arrive at a differential layer a distance x beneath the surface is $\exp(-\alpha \rho x \sec\phi_1)$, where α is the mass absorption coefficient of the medium for the primary photon energy. Combining this fact with Eq. (5), and remembering that the path length through the differential layer is $\sec\phi_1 dx$, the probability of scattering by the differential layer in the direction θ, per unit solid angle is

$$\frac{d\sigma}{d\omega} N_o \rho \left(\sum \frac{\Psi_i Z_i}{A_i} \right) (\sec \phi_1) \left[\exp(-\alpha \rho x \sec \phi_1) \right] dx$$

Multiplying this relation by the transmission over the slant path length $x \sec \phi_2$, viz., $\exp(-a'\rho x \sec\phi_2)$, gives the combined probability of scattering from the layer and subsequent emergence from the surface. Finally, integration over all differential scattering layers must be performed to obtain the reflection coefficient γ for the thick scatterer. Thus $\gamma = \int_0^\infty P\,dx$ which gives

$$\gamma = \left[\frac{d\sigma}{d\omega}\right]_{\theta=\phi_1+\phi_2} N_o \rho \sec\theta_1 \left[\sum \frac{\psi_i Z_i}{A_i}\right] I \tag{6}$$

where

$$I = \int_0^\infty \exp\left[-\rho x (a \sec\phi_1 + a' \sec\phi_2)\right] dx$$

and a' is the absorption coefficient of the medium for the energy of the scattered photon. For a medium consisting of several elements

$$a = \sum \psi_i a_i$$

$$a' = \sum \psi_i a'_i$$

where the a_i's are the mass absorption coefficients for the constituent elements. Integration of Eq. (6) gives

$$\gamma = \left[\frac{d\sigma}{d\omega}\right]_{\theta=\phi_1+\phi_2} N_o \sec\phi_1 \frac{\sum \frac{f_i Z_i}{A_i}}{(a \sec\phi_1 + a' \sec\phi_2)} \tag{7}$$

It is of interest to note that the reflection coefficient is independent of density, but is composition dependent. Further it should be pointed out that this result may be applied directly for the purpose of calculating backscatter counting rates only for the case where the surface-to-detector distance is large compared to $1/\rho(a + a')$, for in this case the scattering source is in effect "thin", and the same solid angle (back to the detector) applies for all differential layers of scattering material. For $\theta = 180^o$, and E = 60 kev for example, and assuming $\rho = 3.34$ grams/cm^3, $1/\rho\,(a + a')$ .38 cm. Hence, at this energy, and at lesser energies, the condition above is easily satisfied.

Eq. (7) may be simplified for case of $\theta = 180^o$ (direct backscatter, appropriate for source-to-detector separation small compared to source-to-surface distance) by noting that in this case $\phi_1 = \phi_2$, so that

$$\gamma = \left[\frac{d\sigma}{d\omega}\right]_{\theta=180^o} N_o \frac{\sum \frac{f_i Z_i}{A_i}}{(a + a')} \tag{8}$$

Figure 6 shows a plot of Eq. (3). This data was used in calculating Compton cross sections as a function of primary photon energy (Eq. (4)) and this result is shown in Figure 7. It is seen that the variation in $d\sigma/d\omega$ (at $\theta = 180^{\circ}$) with energy is relatively mild in the range considered. On the other hand the absorption coefficients for likely elements in the lunar surface vary quite rapidly with energy as shown in Figure 8. This will be the dominant effect in determining the energy dependence of γ. Assuming a lunar surface composition of 47% oxygen, 28% silicon, 11% magnesium, 9% iron, and 5% aluminum, the reflection coefficient for $\theta = 180^{\circ}$ was calculated from Eq. (8), and the result is shown in Figure 9.

E. Error Analysis for Gamma Backscatter System and Source Strength Requirements

As shown previously the counting rate will vary inversely as the square of the altitude. The constant of proportionality involves the reflection coefficient which in turn is composition dependent. Since the composition is not known it is not possible to accurately measure altitude on the basis of counting rate alone. It is, however, apparent that if an initial starting altitude (h_o) is accurately known, as from low altitude radar*, this information may be coupled with backscatter counting rate to determine altitude. This is possible conceptually since at the known altitude h_o counting rate provides a measure of the backscatter coefficient. This coefficient then may be used at lesser altitudes to derive altitude from counting rate data.

In practice it would not be necessary to perform the computation of the reflection coefficient but altitude could be derived from the ratio of

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* Accuracy is said to be ± 1 ft. at an altitude of 50 ft. and deteriorates at lesser altitudes.

the counting rate at any altitude to the counting rate at h_o. This is shown below, and the error analysis appropriate to such a system is evolved. Let

$$S = \text{counting rate at altitude } h$$

$$S_o = \text{counting rate at altitude } h_o$$

Then

$$S = k/h^2$$

$$S_o = k/h_o^2$$

where $k = (\pi/6)\gamma q R^2(1 - \cos^3\theta_{max})$, see Eq. (2), Section II-C. It follows that

$$h = h_o (S_o/S)^{1/2} \tag{9}$$

Basically, the error in the determined value of h will be the result of the separate errors in h_o, S_o, and S. The counting rates will have a certain statistical uncertainty determined by the number of counts accumulated in an integration time T, and will also be in error due to a time lag effect which results from the use of an integrating time constant. The error in h_o will be considered to have statistical significance so that it adds statistically with the random fluctuations of S_o and S. The time lag error is not random but systematic so that it will simply be added to the total statistical error. The over-all error then should be stated as being the time lag error in h ± the total statistical error in h. The magnitude of the over-all error will then not exceed the sum of the two types of errors, except at those times when the counting rates exceed some acceptable number of standard deviations from their proper average values. It is obviously necessary that the acceptance level be specified. For example, if we accept one sigma limits, the derived value of h will be outside this limit 34% of the time, where as for two sigma limits the derived value of h will be outside the limit only 5% of the time. It is suggested that a one sigma limit probably does not represent an adequate confidence level for this application, and that on the other hand 95% confidence limits (2 sigma) are probably unnecessarily high. It will be assumed that 1.5 sigma limits, corresponding to 86.6% confidence are acceptable.

The over-all error will be derived and from this expression, and the known acceptable over-all error, values of the integrating time T and the required k will be determined. The latter will then lead to source strength and counting rate requirements.

The r.m.s. (one sigma) statistical error in h may be found in the usual manner from

$$\sigma^2 h = \left(\frac{\partial h}{\partial h_o} \Delta h_o \right)^2 + \left(\frac{\partial h}{\partial S_o} \sigma S_o \right)^2 + \left(\frac{\partial h}{\partial S} \sigma S \right)^2$$

where Δh_o is the error in h_o ($\pm$ 1 ft) and the σS's are the derivations in the counting rates. This may be evaluated from Eq. (9). The result is

$$\sigma^2 h = \frac{h^2}{4} \left[\left(2 \frac{\Delta h_o}{h_o} \right)^2 + \left(\frac{\sigma S_o}{S_o} \right)^2 + \left(\frac{\sigma S}{S} \right)^2 \right] \qquad (10)$$

Since $\sigma S_0/S_0 = 1/\sqrt{S_0 T}$ and $\sigma S/S = 1/\sqrt{ST}$, Eq. (10) may be written

$$\sigma^2 h = \frac{h^2}{4}\left[\left(2\frac{\Delta h_o}{h_o}\right)^2 + \frac{1}{kT}(h_o^2 + h^2)\right]$$

The fractional statistical error associated with a one sigma error in h is $\delta h_S \equiv \sigma h/h$, and for 1.5 sigma confidence limits $\delta h_S = 1.5\,\sigma h/h$. Hence,

$$\delta h_S = .75\left[4\left(\frac{\Delta h_o}{h_o}\right)^2 + \frac{1}{kT}(h_o^2 + h^2)\right]^{1/2} \qquad (11)$$

The time lag error will now be found. It will be assumed that the descent velocity v is constant. The "memory" contains information having varying degrees of outdatedness. The newest counting rate information is correct, the oldest a time T old. The average age of the information is, therefore, T/2. In a time T/2 the vehicle travels a distance vT/2. If altitude were derived from the number of counts in the memory at any time the altitude error due to time lag would then be vT/2 and the fractional error would be vT/2h*. However, in the present case, altitude is determined from both S_o and S and since $S = S_o$ at $h = h_o$ there is no time lag error at h_o. The time lag error at any h is therefore

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* It may be shown that this is an approximation to the exact value which is given by $(1 + \frac{vT}{h})^{1/2} - 1$. Series expansion gives $\frac{vT}{2h} - \frac{1}{8}(\frac{vT}{h})^2 + \frac{1}{48}(\frac{vT}{h})^3 - \ldots$ Hence, if v << h, the result above is valid.

$$\delta h_{TL} = \frac{vT}{2} \left(\frac{1}{h} - \frac{1}{h_o} \right) \qquad (12)$$

The total error δh_{TOT} is given by

$$\delta h_{TOT} = +\delta h_{TL} \pm \delta h_S \qquad (13)$$

As may be seen from Eqs. (11) and (12) the total error at any altitude h is a function of the primary variables k and T. $\Delta h_o/h_o$ is fixed at 1/50, and v may be taken as the maximum vertical velocity (10 ft/sec). The parameters k and T are to be chosen such that the total error will lie within the acceptable error corridor over the altitude range of 0 to 50 ft. This may be done by solving the two simultaneous equations [of the type of Eq. (13)] which result by letting the total fractional error be 0.05 at h = 20 ft. and at h = 50 ft. The choice of h = 50 ft. is clear since this represents the altitude at which the greatest error occurs. Below 20 ft. the acceptable error is constant, viz. ± 1 ft., while the actual measurement error will diminish. Thus, if the acceptable error at 20 ft. and 50 ft. is achieved, the total error over the whole altitude region of interest will be acceptable. When this procedure is followed it is found that T = .048 seconds and k = 3.64×10^7 (photons/sec)(ft^2). Use of these conditions will lead to the minimum source strength requirements. Assuming these values of k and T the altitude error has been calculated for the case of a vertical velocity of v = 10 ft/sec. The result is shown in Figure 10.

Source strength requirements may be found from the value of k specified above. Since $k = (\pi/6)\gamma q R^2 \left[1 - \cos^3\theta_{max} \right]$,

$$q = \frac{6k}{\pi \gamma R^2 \left[1 - \cos^3 \theta_{max} \right]} \quad \text{photons/sec}$$

Assuming $\gamma = 1.91 \times 10^{-2}$ per steradian (60 kev photons), $\theta_{max} = 70^{\circ}$, and a detector whose radius R is 2.5 inches, it is found that $q = 8.73 \times 10^{10}$ photons/sec. Since 1 curie gives 3.7×10^{10} disintegrations per second, the required source strength (assuming one photon/disintegration) is about 2.36 curies. This also assumes negligible source self absorption and a detector efficiency of 100%. Source strength would have to be increased somewhat depending upon these factors for an actual device. This will be discussed in Part H of this Section of the report.

Utilizing the value of k found previously it is also possible to specify counting rate requirements, since $S = k/h^2$. A plot of counting rate as a function of altitude is shown in Figure 11.

F. Tolerable Thickness of Dust Cloud For Gamma Backscatter System

For a gamma backscatter system to be affected negligibly due to attenuation in the dust cloud it is necessary that the two-way transmission through the cloud be less than unity by an amount which is small compared to the statistical uncertainty of the counting rate. The counting rate as a function of altitude is $S = k/h^2$, where h is the altitude in feet, and k was determined to be 3.64×10^7 (photons/sec)(ft^2). The fractional statistical error in counting rate for 1.5 sigma confidence limits is $\delta S = 1.5/\sqrt{ST}$ where T is the time constant, which was found to be

.048 seconds. Hence, $\delta S \doteq 1.5 h/\sqrt{kT} = 1.13 \times 10^{-3} h$. The two-way transmission T is given by $T = \exp\left[-(\alpha + \alpha') \int_0^h \rho(h)\, dh \right]$, where α and α' are respectively the mass absorption coefficients of the dust for the primary and secondary gamma ray energies, and where $\rho(h)$ is the density of the dust cloud at altitude h. Now $1 - T$ must be a small number so that T must be close to unity. Therefore, $(\alpha + \alpha') \int_0^h \rho(h)\, dh$ must be small. For small exponents $e^{-x} \doteq 1 - x$. We may, therefore, take $T = 1 - (\alpha + \alpha') \int_0^h \rho(h)\, dh$. The requirement of negligible attenuation is satisfied if $1 - T \leq .1 \delta S$. The maximum tolerable thickness (in terms of weight per unit area for a given linear thickness h) may then be found by solving the equation

$$1 - T = 1.13 \times 10^{-4} h$$

for the integral $\int_0^h \rho(h)\, dh$. Substitution of the approximation for T, i.e. that $1 - T \doteq (\alpha + \alpha') \int_0^h \rho(h)\, dh$ leads to the result that

$$\int_0^h \rho(h)\, dh = \frac{1.13 \times 10^{-4} h}{(\alpha + \alpha')} \qquad (14)$$

If a probable dust cloud model could be postulated it would then be possible to perform the integration, and the minimum acceptable primary photon energy would be the energy at which $1.13 \times 10^{-4} h/(\alpha + \alpha')$ is just equal to the integral, i.e. the actual total dust cloud weight per unit area for the altitude of interest. This type of description of the tolerable dust cloud thickness (integrated weight per unit area) is necessary since ρ undoubtedly would be a function of h. Some immediate impression of tolerable dust cloud density may be obtained if a uniform (with h) density is assumed. Then $\int_0^h \rho\, dh = \rho h$, and from Eq. (14)

$$\rho = \left[1.13 \times 10^{-4} (ft^{-1})\right]\left[1/30.48\,(ft/cm)\right] / (a + a')\ gram/cm^3.$$

This result is shown in Figure 12. The dust composition assumed is the same as that previously assumed for the lunar surface composition. If we further assume that the dust cloud is a hemisphere of 50 ft radius, then it may be shown that 37 lbs of dust would give the tolerable density of 4.7 μ grams/cm^3 for a 60 kev primary gamma ray system. If the lunar surface dust has a density of 3.34 grams/cm^3, then 37 lbs of dust would correspond to volume of 0.565 ft^3 of dust removed from the surface. If the removed layer was only 1/8 inch thick, the involved surface area would be 54.24 ft^2, which in turn could correspond to a circle whose diameter is 8.31 ft. It does not seem unreasonable to expect that this much dust would be removed due to exhaust gas impact, but in the absence of specific dust cloud data positive statements about the suitability of a 60 kev (or lesser) primary gamma energy can not be made. About all that can be concluded is that a higher energy should be considered if dust cloud data becomes available and the 60 kev system is found inadequate on this account.*
It is emphasized, however, that due to the larger shielding weight required for high energy sources, the lower energy source is preferred. Hence, the high energy system should be considered only as the result of necessity.

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* Note: It has been reported that the latest "official" NASA opinion is that the surface is covered with only a very thin layer of dust and that this will be cleared away by the first rocket blast. Thereafter, a dust cloud will not exist.

G. The Use of High Energy Gamma Radiation

For the sake of completeness some attenuation calculations were made for higher photon energies. Cesium-137 (662 kev) is ideal since it is available at high specific activity, and is inexpensive. Its half-life of 30 years is more than adequate for this application. For 180^o back-scatter the energy of the secondary (Compton) photon is 184 kev. The absorption coefficient α for the primary energy is about 0.077 cm^2/gram while the coefficient α' for the secondary gamma is 0.128 cm^2/gram, whence $\alpha + \alpha' = 0.205$ cm^2/gram. For the Am-241 (60 kev) system, $\alpha + \alpha' = 0.786$ cm^2/gram. Therefore, for the Cs-137 system the maximum tolerable dust cloud density is 0.786/0.205 = 3.83 times that which applies for the Am-241 system, viz. ~ 18 μ gram/cm^3 assuming the same dust cloud conditions previously used for illustration.

While a distinct improvement is effected, it is not so large that it can clearly be said that dust cloud attenuation may be neglected. As before, firm conclusions can only be made if specific dust cloud conditions can be named.

It is clear that going to still higher energy, e.g., C0-60 (1.17 and 1.33 Mev), will render only a mild additional improvement since the energy of the backscattered photons are 210 kev and 214 kev - not much higher than the 184 kev photon energy for the Cs-137 backscatter system.

The reflection coefficient for Cs-137 photons is similar to that which applies for Am-241 photons so that the source strength requirements are also similar.

H. Source Selection and Shielding Requirements

The desirable features of the gamma emitter for this application are that the energy of the photons be small enough so that the necessary shielding is lightweight, but large enough so that the reflection coefficient is favorable and dust and gas cloud attenuation is negligible. If the dust cloud problem does not exist as indicated by MSC, the requirements are satisfied by the isotope Americium-241. Decay is by emission of alpha particles, but gamma rays of several energies accompany the process. The intensities in terms of gamma rays per disintegration are given below. *

	Photon Energy (kev)	Intensity (%)
	26.4	2.5
	33.2	0.11
	43.4	0.073
	59.6	35.9
	99	0.023
	103	0.019
L x-rays	11.9 to 22.2	37.6

* Intensities of X-Ray and γ Rays in Am-241 Alpha Decay, L. B. Magnusson, Physical Review, Vol. 107, No. 1, July 1, 1957, p. 161.

The alpha particles of course would not be detected since they would not penetrate sturdy source and detector windows. The only significant x and gamma rays are the 59.6 kev line and the L x-rays. The latter, however, will be more easily absorbed in source and detector windows, and will in addition have a lower reflection coefficient. For this application, therefore, we may regard Am-241 as a pure 59.6 kev gamma ray emitter, where 35.9% of the disintegrations give rise to photons of this energy.

The half-life of this isotope is 458 years. It is presently available in the form of $Am^{241}O_2$ at a specific activity of 2.8 curies per gram. The present limit per license is 10 grams, and the cost of the oxide powder is $1500 per gram.

Am-241 sources in curie strength have never been fabricated, so far as we can determine, probably because there has never been any need for them. Very small sources of the pure element have been made by evaporation from a hot filament, and millicurie strength sources made from the powder can be purchased.* Apparently techniques for making large sources either are available or can be worked out. We checked with one company just to see if they might be willing to undertake fabrication of a several curie source of Am-241, and received an affirmative reply.

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* For example from Western Radiation Laboratory, Los Angeles, California.

The useful output of the source will be less than 35.9% of the disintegration rate due to source self-absorption, and source window absorption. An estimate of activity contained in the source to be equivalent to the ideal (1 photon per disintegration) point source requirement of 2.36 curies will be made. This must be regarded only as an estimate since data for the density and absorption coefficient of Americium could not be found. A plot of mass absorption coefficient vs. Z (atomic number) for the elements Tungsten (Z = 74), Platinum (Z = 78), Thallium (Z = 81), Lead (Z = 82), and Uranium (Z = 92) was made and extrapolation to Americium (Z = 95) gave 11.4 $cm^2/gram$. If the density of the element is assumed to be equal to that of Uranium (18.7 $grams/cm^3$) then the linear absorption coefficient μ is 11.4 x 18.7 = 213 cm^{-1}. For a disk shaped source whose thickness is small compared to its diameter the efficiency, as compared to an ideal windowless point source which emits one photon per disintegration, is given by

$$Eff = \frac{i}{\mu t}\left[1 - e^{-\mu t}\right] \exp(-\mu_w t_w)$$

where i is the intensity (photons per disintegration = .359 for 59.6 kev photons from Am-241), t is the thickness of the active material, and where μ_w and t_w are the linear absorption coefficient and the thickness of the window material. If we assume a 2 mil thick deposit of Americium and a sturdy stainless steel window (μ_w = 8.7 cm^{-1}) 10 mils thick it is found that Eff = .194 or 19.4%. The actual quantity of radioactivity required would then be 2.36/.194 = 12.2 curies. This in turn would require

4.35 grams of active material at 2.8 curies per gram. Assuming a density of 18.7 grams/cm^3, the volume would be 0.232 cm^3. For a 2 mil thick layer the area is 45.7 cm^2. The source diameter then is about 3 in. Thus, the physical size of the source appears reasonable.

Since the source will be mounted next to the detector, a shield must be used between the two units to prevent direct detector irradiation. The transmitted gamma rays must cause a contribution to the detector response which is small compared to one standard deviation of the smallest net signal counting rate. It may be shown that a 1/4 inch thick lead shield will do this. Thus, if a lead disk 3-1/2 inches in diameter and 1/4 inch thick is used (with the source exposed at the lower side, but slightly recessed from the bottom of the disk) adequate shielding will be achieved at the sides and top of the disk. The weight of such a shield would be about one pound.

While this shield is designed to prevent direct irradiation of the detector, it would also provide more than adequate shielding for vehicle occupants provided that the unit actually is mounted in such a position as to be located between the source and the occupants.

It is worthwhile to estimate the shielding required to protect personnel not favorably positioned with respect to this shield. The MSC requirement was stated as 2 mr/hr at 10 ft. Actually the vehicle wall itself would provide some shielding, but this will be ignored. Source self-absorption will also be ignored. It may be shown that the dose rate in mr/hr at a distance of x cm from a point source of N photons per second of energy E kev, with a shield thickness t_S between source and observer is given by

$$DR = \left(\frac{5.47 \times 10^{-6}}{x^2}\right) N E \alpha_a \exp(-\mu_s t_s) \qquad (15)$$

where α_a is the mass absorption coefficient of air at photon energy E, and μ_s is the linear absorption coefficient of the shielding material at energy E. Using Eq. (15) it may be shown that 1/16 inch is adequate. If this thickness is used as a source cover it would add 25% to source shield already illustrated since it would have the same area and 1/4 the thickness. Hence, total shielding requirements would be about 1-1/4 lbs.

I. Background Considerations

Any radiation technique of measurement is subject to some degree to the influence of natural or other backgrounds. These unwanted components of the detector response must either be rendered insignificant as compared to the signal, or provision must be made to measure these components with adequate precision so that background correction is meaningful.

The sources of background radiation in the present application are of three types: (1) primary cosmic and solar corpuscular radiation, (2) secondary radiation caused by activation of the lunar crust, and (3) naturally occurring radioactive elements in the surface material.

While much remains to be determined concerning each of these sources, sufficient information exists to establish whether or not the background influence will be a major problem. We shall endeavor to set an upper limit on the possible background counting rate, and then compare this to required signal rates to determine its significance.

The primary cosmic radiation refers to energetic radiation originating at regions remote from the solar system, consisting for the most part of stripped nuclei which have been injected into intergalactic space. This radiation is essentially isotropic in space and its magnitude is essentially constant in time. The intensity has been measured several times, the experiment of Pioneer IV perhaps being best known. The interplanetary cosmic ray intensity is about $2/cm^2$ sec. Solar corpuscular radiation (excluding the low energy protons of the normal "solar wind" which would not be detected) is included in this figure, although the contribution from the sun may increase tremendously during large solar flares. Landings at such times, of course, would not be planned. Now the detector may be grossly insensitive to this energetic radiation so that actual count rates cannot easily be calculated, but it is clear that an upper limit is $2/cm^2$ sec. There will also be an x-ray flux from the sun but these photons will not be detected since their energy is less than 2 kev, and are easily shielded with a very thin window. The cross sectional area of the detector measured in a plane parallel to the surface may be used for count rate estimates. Assuming a detector of 5 inch diameter, as previously mentioned for the gamma backscatter altimeter, the cross sectional area would be ~127 cm^2. Class (1) radiation then could not contribute more than 254 counts per second.

Class (2) radiation will be chiefly gamma rays which were caused by n, γ reactions in the crust, where the neutrons are the result of cosmic particle bombardment. An estimate of this gamma flux has been made by Barton*, and is 0.6/cm^2 sec at the lunar surface. If we double this estimate, since all possible interactions could not possibly be considered, a resultant count rate of 152 counts per second is found. Again this response is probably high since the energy of most of these gamma rays would be greater than 1 mev, and the detector could be made quite inefficient at these energies simply by choosing an appropriate thickness.

Finally, the natural background from radioactivity in the crust must be considered. All estimates of this contributor are equal to or less than the Earth's natural background, so that the latter may be used as an upper limit. It would be expected that the activity would come largely from uranium (U-235 and U-238), thorium, in equilibrium with their daughter products, and potassium-40. Experience with unshielded scintillation packages approximating the detector assumed here leads to an estimate on the Earth's surface, and hence also on the moon, of not greater than 120 counts per second (for integrated response above 40 kev).

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* "An Estimate of the Nuclear Radiation at the Lunar Surface," John A. Barton, Presented at the 6th National Annual Meeting of the American Astronautical Society, January 1960.

The total comes to 526 counts per second. With an integrating time of .048 seconds, appropriate for the backscatter gauge, this comes to 25.2 counts. The minimum count rate requirement for this system (at an altitude of 50 ft.) is $\sim 1.5 \times 10^4$ per second, which would give a count accumulation of 720. One standard deviation of this number is $\sqrt{720} \approx 26.8$ counts. Hence, at worst, the background effect is comparable to one standard deviation of the least signal to be expected. At worst, therefore, some simple means of background reduction may be required. At best, none will be needed. While it appears that a more detailed look is necessary to establish whether or not the background influence can be completely ignored, it is clear that this "noise" definitely will not render the system unfeasible.

J. Detector Selection

The selection to be made here is not intended to be final, for a more detailed engineering study could lead to revisions. It is only intended to show that it is possible to make a selection which appears feasible. A natural choice for the gamma ray energy of interest here is the scintillation detector since high efficiencies are readily obtained.* A thin sodium iodide or cesium iodide crystal, coupled with a low noise ruggedized multiplier phototube could constitute a workable arrangement. The crystal could be thin to produce a drop in its efficiency at higher

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* Gas filled detectors could be used if filled to very high pressure, although such detectors would have to be specially developed.

energies, which would aid in background reduction. An aluminum window of appropriate thickness would produce a low energy cut off, say at 5 kev, which would make the device insensitive to low energy solar x-rays. The photon efficiency distribution for an example window-crystal combination is shown in Figure 13.

It would not be necessary that the crystal (5 in. diameter has previously been assumed) be a single piece, but the area could be achieved with a mosaic of smaller pieces with only a moderate reduction in light output.

The phototube should not be a problem with respect to environmental specifications. The Model 543A ASCOP tube, for example, has the following specs:

Shock: 50 g, 11 milliseconds duration

Vibration: 20 g, up to 3000 cps.

Max. Temperature: 75°C

If NaI or CsI crystals are used, pulse counting techniques probably are not feasible since maximum required counting rates are in excess of 10^6 per second and the respective flash times of these phosphors are 0.25 microsecond and 1.1 microseconds. Because of the random variation in the counting rate about its average value, "pile up" would occur. Two alternatives may be suggested. A plastic scintillator (flash time, 5 nanoseconds) could be employed so that pulse counting is possible, or response could be obtained by measuring phototube anode current. It is easily calculated, for example, that 10^4 counts per second of 60 kev photons for a NaI crystal and the tube above would give a photocathode current of about 2×10^{-13} amperes. With a multiplier gain of 10^6 (which would require a high voltage of about 2100 volts) the anode current would be 2×10^{-7} amps. This current flowing in a 100,000 ohm anode resistor would give .02 volts. At the highest required counting rates ($\sim 10^7$/sec), the signal would be 20 volts. The tube has its own dark current which must be considered. The photocathode dark current is quoted as being 5×10^{-15} amperes, only 2.5% of the minimum signal. This could, of course, be subtracted out. Gain stability of this tube is said to be excellent. Typical stabilities of less than 5% variation over 48 hours with a 10^{-7} amp anode current have been observed, according to the manufacturer. Long term stability is not required since the whole measuring time is a few seconds to a few minutes. The ratio technique of altitude derivation would automatically take care of gain variation on a long term basis.

The detector unit, including a lightweight housing, probably would weigh about 4 lbs, so that the source and detector together could weigh about 5-1/4 lbs. The weight of the associated electronics probably can be made commensurate with the weight of the measurement head.

III. Direct System

A. General Consideration

The title above refers to systems where direct radiation from a source, rather than secondary radiation from the lunar surface, is used as the means for altitude sensing. A system was suggested by MSC and described in detail as regards operational concepts. It will be appropriate to briefly restate these concepts. Several gamma sources would be ejected at an altitude of about 100 ft. and allowed to free fall to the surface. The sources would emit photons of differing energy making it possible to distinguish them on a pulse height basis with the usual gamma spectrometry techniques. A detector array would be associated with each source. Counting rate information from the central detector of each array would be used to determine source-detector array slant distance. Several highly collimated detectors surrounding each central detector would be used as "directional locator" sensors, and an associated servo system using signals from these sensors would keep the array properly aimed. Thus, with slant distance and angle from the vertical, maintained by a gyro-stabilizing unit, it would be possible to calculate altitude for a single source-detector array combination. The use of several sources would provide several altitude indications which could be averaged. The system can be thought of as the radiation analog of an automatic optical tracking system. The success of the latter does not, however, establish the feasibility of its radiation counterpart because of very important fundamental differences. Primarily the accuracy of a radiation system is governed by consideration of photon counting rate statistics, whereas in nearly all optical systems light levels are sufficiently large that the number of photons in any practical response time is a huge number. Hence, statistical errors are negligible compared to all others. It is tempting to suppose that the statistical error in altitude determination for the radiation system above is associated only with the random fluctuations in counting rate of the central detector (which measures slant distance). A more critical situation, however, exists with regard to the angular locator system. When the positioning is correct the peripheral detectors receive no signal at all, and corrective action is to occur when this starts to depart from zero by a small amount, i. e. when the source just starts to become visible at the edge of the detector's field of vision. Now this position is exceedingly unfavorable since the geometric efficiency distribution (as a function of position) is zero at the edge of the detector field of vision and then does not abruptly increase to maximum value but rather steadily increases in that direction. The significance of this fact is that in order to get good angular information a very large source strength is required. At first glance, it would appear that the direct system necessarily requires far less source strength than the backscatter system, but this is not the case since to assume this is to ignore the statistics of the angular location problem.

Actual source strength requirements will be worked out in some detail below so that a comparison can be made with the backscatter system. Before proceeding to do this, however, some further aspects of the comparison philosophy should be mentioned. It is obvious of course, that the physical size, weight, and complexity of the direct system exceed those of the gamma backscatter device. Advantages for the direct system, if any, must, therefore, derive from the fact that it would either be more reliable or would require significantly less source strength. As previously indicated, the potential problem of composition dependence for the backscatter gauge can probably be avoided quite successfully by use of a ratio technique where in counting rate information at a known altitude (from low altitude radar at 50 ft.) establishes the proper scale factor. If this technique is indeed adequate, both direct and indirect systems have equal validity with regard to principle. Concerning functional reliability it is clear that the much simpler backscatter system would have a distinct advantage. This leaves the source strength comparison as the remaining factor. It is emphasized, however, that the source strength requirements for the backscatter system are not objectionable in terms of either weight or volume. Consequently, this aspect of the comparison is significant only if the direct system actually requires more source strength, and in this case all factors would weigh in favor of the backscatter approach.

B. System Simplification and Geometry

Before performing error analysis it is well to simplify the system conceptually as far as possible. This not only makes the analysis more straightward, but also would reduce the number of working parts - which of course is desirable.

At the outset let it be recognized that the angular location system is unnecessary from the viewpoint of minimum information requirements. Thus, consider three nondirectional detectors located in a plane parallel to the landing surface at a distance h, as shown in Figure 14. For convenience let the origin of the reference frame be taken on the surface at a point directly below the center of the vehicle on which the detectors are mounted. Let the landing surface be coincident with the X-Y plane. The source may be located at the general position (x, y, 0) while the location of the three detectors may be given as (x_1, y_1, h), (x_2, y_2, h), and (x_3, y_3, h). Each of the three detectors is a different (usually) distance from the source. Let the distances be labeled L_1, L_2, and L_3. The three detector counting rates may be written

$$s_1 = k_1/L_1^2$$

$$s_2 = k_2/L_2^2$$

$$s_3 = k_3/L_3^2$$

where the k's are given by

$$k_i = \frac{\epsilon_i A_i}{4\pi} q$$

ϵ_i being the detector efficiency, A_i the detector area, and q the source strength in terms of emanations per unit time. Since

$$L_1^2 = (x_1 - x)^2 + (y_1 - y)^2 + h^2$$

$$L_2^2 = (x_2 - x)^2 + (y_2 - y)^2 + h^2$$

$$L_3^2 = (x_3 - x)^2 + (y_3 - y)^2 + h^2$$

the three response equations constitute a complete set with only three unknowns (x, y, and h). They may be solved - in particular for h. Thus, conceptually a basic triangulation system exists and the angular locator system is evidently unnecessary. It is necessary, of course, that the distance between detectors is a reasonable fraction of h so that adequate sensitivity to source position can be achieved. In practice, the equations would have to be solved continuously by a computer. It is of interest to note that three detectors are required to be able to determine the location of a single source. In the original system (employing the angular locator) a single array was required for this purpose. This array, however, would require a central detector and at least three auxiliary detectors to keep the angle properly adjusted and measured. The statistics of altitude determination for the original system would therefore be influenced by the statistical fluctuations of at least four count rates, as opposed to three for the simplified system. Moreover, because of the high degree of collimation employed in the original angular locator system, these detectors are very inefficiently used. It is, therefore, reasonable to expect that the simplified system would, in addition to the advantages already named, require less source strength.

where the σ's represent one standard deviation of the associated quantities, and $\sigma_i N_i = \sqrt{N_i}$.

Evaluation leads to

$$\sigma h = \frac{T}{2h} \left\{ \frac{k_1^2}{N_1^3} [1]^2 + \frac{k_2^2}{N_2^3} [2]^2 + \frac{k_3^2}{N_3^3} [3]^2 \right\}^{1/2} \qquad (16)$$

where the symbols in the square brackets are defined by

$$[1] = 1-2 \left\{ T \left[\frac{k_1(A^2+E^2)}{N_1} + \frac{k_2(AB+EF)}{N_2} + \frac{k_3(AC+EG)}{N_3} \right] + A(D-x_1) + E(H-y_1) \right\}$$

$$[2] = -2 \left\{ T \left[\frac{k_1(AB+EF)}{N_1} + \frac{k_2(B^2+F^2)}{N_2} + \frac{k_3(BC+FG)}{N_3} \right] + B(D-x_1) + F(H-y_1) \right\}$$

$$[3] = -2 \left\{ T \left[\frac{k_1(AC+EG)}{N_1} + \frac{k_2(BC+FG)}{N_2} + \frac{k_3(C^2+G^2)}{N_3} \right] + C(D-x_1) + G(H-y_1) \right\}$$

In order to make quantitative predictions source and detector locations will be assumed. At a given altitude, and for a given detector arrangement, the counting rates and accuracy will diminish as the source is moved farther and farther from the origin. A source-to-origin distance of 25 ft. was suggested by MSC. A distance of 21 ft is somewhat more favorable and will be assumed here. With this distance fixed, accuracy will also vary somewhat with the angular location (in the X-Y plane) of the source. It will be assumed that the source is positioned on the X axis. The detectors will be placed on a circle of 14 ft diameter, with equal angular separation. Detector #1 will be located directly above the X axis. Then let a = radius of the detector circle. The position co-ordinates of the source and detector are then given by:

Detector #1	$x_1 = a = 7$ ft.	
	$y_1 = 0$	
	$Z_1 = h$	
Detector #2	$x_2 = -a/2 = -3.5$ ft.	
	$y_2 = +(\sqrt{3}/2)a = +6.06$ ft.	
	$Z_2 = h$	
Detector #3	$x_3 = x_2 = -a/2 \doteq -3.5$ ft.	
	$y_3 = -y_2 = -(\sqrt{3}/2)a = -6.06$ ft.	
	$Z_3 = h$	
Source	$x = 3a = 21$ ft.	
	$y = 0$	
	$Z = 0$	

It may then be verified that

$$\Delta = -3\sqrt{3}\,a^2$$

In order to get several altitude measurements which could be averaged, the same approach must be pursued in both cases, i.e. several sources would be used, each with a different photon energy.

C. Error Analysis and Source Strength Requirements

The number of counts accumulated by any of the detectors in time T is $N = ST = kT/L^2$. It follows that

$$\frac{k_1 T}{N_1} = (x - x_1)^2 + (y - y_1)^2 + h^2$$

$$\frac{k_2 T}{N_2} = (x - x_2)^2 + (y - y_2)^2 + h^2$$

$$\frac{k_3 T}{N_3} = (x - x_3)^2 + (y - y_3)^2 + h^2$$

The solution to these simultaneous equations is

$$x = AQ_1 + BQ_2 + CQ_3 + D$$

$$y = EQ_1 + FQ_2 + GQ_3 + H$$

$$h = \left\{ Q_1 - \left[AQ_1 + BQ_2 + CQ_3 + D - x_1\right]^2 - \left[EQ_1 + FQ_2 + GQ_3 + H - y_1\right]^2 \right\}^{1/2}$$

where

$$A = + (y_2 - y_3)/\Delta$$

$$B = +(y_3 - y_1)/\Delta$$

$$C = +(y_1 - y_2)/\Delta$$

$$D = +\left[(y_1-y_2)(y_2-y_3)(y_3-y_1)-(y_2-y_3)(x_1^2-x_2^2)+(y_1-y_2)(x_2^2-x_3^2)\right]/\Delta$$

$$E = \left[A(x_2 - x_1) - 1\right]/(y_1 - y_2)$$

$$F = \left[B(x_2 - x_1) + 1\right]/(y_1 - y_2)$$

$$G = C(x_2 - x_1)/(y_1 - y_2)$$

$$H = \left[2D(x_2-x_1) + (x_1^2-x_2^2) + (y_1^2-y_2^2)\right]/2(y_1 - y_2)$$

$$\Delta = +2\left[(y_2 - y_3)(x_2 - x_1) - (y_1 - y_2)(x_3 - x_2)\right]$$

$$Q_1 = k_1 T/N_1$$

$$Q_2 = k_2 T/N_2$$

$$Q_3 = k_3 T/N_3$$

The statistical uncertainty (one sigma) in the derived value of h is a function of the separate statistical uncertainties in N_1, N_2, and N_3. This function may be evaluated from the relation that

$$\sigma h = \left[\left(\frac{\partial h}{\partial N_1}\sigma N_1\right)^2 + \left(\frac{\partial h}{\partial N_2}\sigma N_2\right)^2 + \left(\frac{\partial h}{\partial N_3}\sigma N_3\right)^2\right]^{1/2}$$

$A = -1/3a$ $\qquad$ $E = +\sqrt{3}/3a$

$B = +1/6a$ $\qquad$ $F = -\sqrt{3}/2a$

$C = +1/6a$ $\qquad$ $G = +\sqrt{3}/6a$

$D = 0$ $\qquad$ $H = 0$

and that

$A^2 + E^2 = 4/9a^2$ $\qquad$ $B^2 + F^2 = +7/9a^2$

$AB + EF = -5/9a^2$ $\qquad$ $BC + FG = -2/9a^2$

$AC + EG = +1/9a^2$ $\qquad$ $C^2 + G^2 = +1/9a^2$

Further assuming that all detector areas and efficiencies are equal so that $k_1 = k_2 = k_3 = k$, it is found that

$$\left[1\right] = 1 - \frac{2}{9}\left\{\frac{kT}{a^2}\left[\frac{4}{N_1} - \frac{5}{N_2} + \frac{1}{N_3}\right] + 3\right\}$$

$$\left[2\right] = +\frac{2}{9}\left\{\frac{kT}{a^2}\left[\frac{5}{N_1} - \frac{7}{N_2} + \frac{2}{N_3}\right] + \frac{3}{2}\right\}$$

$$\left[3\right] = +\frac{2}{9}\left\{\frac{kT}{a^2}\left[-\frac{1}{N_1} + \frac{2}{N_2} - \frac{1}{N_3}\right] + \frac{3}{2}\right\}$$

From the relations that

$$N_1 = kT/(4a^2 + h^2)$$

$$N_2 = N_3 = kT/(13a^2 + h^2)$$

the square bracket quantities are evaluated to give

$$\lfloor 1 \rfloor = +25/3$$

$$\lceil 2 \rceil = -89/7$$

$$\lceil 3 \rfloor = +21/9$$

Remembering that $1.5\,\sigma$ rather than 1σ confidence limits are desired, substitution into Eq. (16) yields

$$1.5\,\sigma h = \frac{a^3(4+\lambda)^{3/2}}{4h(kT)^{1/2}} \left[625 + 890\left(\frac{13+\lambda^2}{4+\lambda^2}\right)^3\right]^{1/2} \qquad (17)$$

where $\lambda \equiv h/a$. This expression may be used to evaluate the statistical error for any set of conditions imposed. It should be remembered that $x = 3a$ has already been "built into" the result above so that one can not now vary "a" while leaving x fixed. One may determine source strength to give a desired accuracy and determine count rate and error as a function of altitude.

Before proceeding the time constant will be optimized. The counting rate data will always be behind by a time $T/2$ so that the associated time lag error is $vT/2$. This will be constant independent of altitude if the speed v is constant. One desires that the total error, statistical plus time lag, does not exceed an acceptable value, say Δh. Denoting the complete coefficient of $(kT)^{-1/2}$ in the right hand member of Eq. (17) by β the combined error is

$$\frac{\beta}{(kT)^{1/2}} + \frac{vT}{2} = \Delta h$$

Solving for k gives

$$k = \frac{4\beta^2}{T(2\Delta h - vT)^2}$$

Since source strength is directly proportional to k, we desire k to be minimized. Solution of the equation

$$\frac{dk}{dT} = - \frac{4\beta^2 (2\Delta h - 3vT)}{T^2 (2\Delta h - vT)^3} = 0$$

gives the optimum T, viz.

$$T_{opt} = \frac{2\Delta h}{3v}$$

Note that this optimum is independent of altitude. The optimum is quite broad as shown in Figure 15. The value of T should be selected for the largest vertical velocity which may occur, i. e. 10 ft/sec. Since (at the low altitude end) the total tolerable error (Δh) is one foot, $T_{opt} = 1/15$ sec. The associated time lag error, $vT/2$, is 1/3 ft. This error will be constant with altitude if v is constant. The part of the total error available for statistics is therefore 2/3 ft.

In the altitude range of interest the largest statistical error is at h = 0 so that k must be selected at h = 0 to make $1.5\sigma h = \pm 2/3$ ft. It is evident from Eq. (17) that $1.5\sigma h$ approaches infinity as h approaches zero. This is because of the fact that the detector counting rates approach constant values ($S_1 = k/4a^2$, and $S_2 = S_3 = k/13a^2$) in such a way that the slopes of the S's (dS/dh) approach zero at h = 0. Altitude sensitivity is, therefore, poor at low altitude. To improve the situation, the detector plane should be as far above the vehicle as possible. In this way, when the vehicle is touching the surface the detector plane is a distance h_o above the surface, and $dS/dh \neq 0$. The indicated altitude h' is then always given by $h' = h + h_o$, where h is the true altitude measured from the bottom of the vehicle. The operation $h = h' - h_o$ must be performed as the last step in the automatic computation process. Since h_o is a known constant the error in h is equal to the error in h'. One may determine the required values of k at zero altitude as a function of h_o such that $1.5\sigma h = 2/3$ ft. This is done by setting the right hand member of Eq. (17) equal to 2/3 and solving for k, where the substitutions are made that $h = h_o$, $\lambda = h_o/a$, a = 7 ft., and T = 1/15 sec. The associated source strength requirements in terms of photons per second may then be found from the relation that $q = 4\pi k/\epsilon_i A_i$. This result may be translated into curies by dividing by 3.7×10^{10}, assuming the "ideal" case of one photon per disintegration and no source self-absorption. This has been done assuming $\epsilon_1 = \epsilon_2 = \epsilon_3 = 1$, and $A_1 = A_2 = A_3 = .182$ ft.^{2} This area was selected such that the total area of the three detectors is just equal to the area of the single detector assumed in illustrating the backscatter system. The resulting source strength requirements at zero altitude are shown as a function of h_o in Figure 16. Assuming that the maximum feasible value of h_o is 16 ft.*, it is seen that the required source strength is 3.36 curies. This is to be compared to the (also "idealized") value of 2.36 curies for an ideal point source and no self-absorption calculated for the backscatter system. Source strength requirements are, therefore, virtually identical. Little, if any, source strength advantage is associated with the direct system.

Assuming this value of source strength, counting rates as a function of altitude (measured from the bottom of the vehicle) were calculated and these results are shown in Figure 17. The associated error calculated from Eq. (17) is plotted in Figure 18.

IV. Comparison of Direct and Indirect Gamma Systems

It has been shown that source strength requirements for both direct and indirect systems are similar when a comparison is made on the basis of equal detector areas. This result applies to the simplified direct system which operates on the basis of simultaneous and continuous solution of three response equations to determine altitude. A larger source strength would be required for a direct system in which an angular locator system is employed. The latter system would also require more bulk due to the fact that a larger number of detectors and collimators are necessary, and that provision must be made for a servo control system to maintain proper angular positioning. It is clear that the simplified direct system is a better choice. It is also clear that the indirect system requires less bulk

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* As advised by G. Brandon of MSC.

than the simplified direct system. This is because of the fact that only one detector is required, rather than three, and since the associated computer would be a great deal less complex.

It should be pointed out that there are additional disadvantages to the direct system. First, the fact that the vehicle may have a horizontal component of velocity has been ignored in the calculations. This would mean that the vehicle may be moving laterally with respect to the source after the source has landed. This would increase the source-detector separation and in turn would deteriorate accuracy, or would require still more source strength. A similar situation does not exist for the indirect approach. Also, the direct system would require a source ejection mechanism, whereas the indirect system does not. In addition, the source for the indirect system may be "turned off" after landing simply by rotating a lightweight shield into place. For the direct system vehicle occupants would be exposed to source radiation until the sources were covered, an operation which would have to be done manually, and in any case would have the task of gathering the sources and returning them to the vehicle.

Further, it may well be necessary, in the case of the direct system, to utilize several redundant detectors to avoid the possibility of the vehicle obscuring some of them. This would entail the use of additional automation to select the appropriate detectors. The same situation does not exist for the indirect approach.

The indirect system will also have advantages with regard to pitch and spin. The variation of altitude error with pitch should be less for the scatter approach so that the instrument vertical does not require as rigid a control as would be the case for the direct system. While spin is nominally zero, even a small amount of spin would require a reduced time constant and hence greater source strength for the direct system. Spin obviously does not affect source strength requirements for the indirect system.

It, therefore, appears that the advantages associated with the indirect (backscatter) gamma system recommend it, above all others, as being the most promising system. It is true that auxiliary information at some starting altitude, as from low altitude radar at 50 ft., will be necessary to avoid the surface composition problem; but since such a device will be aboard anyway, and since its accuracy is acceptable (in terms of induced error at lower altitudes) this should not be objectionable.

It is recognized that in overall systems design it is better not to have the correct operation of one system depend on that of another. However, even if the appropriate starting altitude is not available due to failure of the radar altimeter, the gamma backscatter altimeter will provide usable altitude data although the error may be larger. The expected variations of lunar surface composition are not yet known but will probably be available before the manned landing. Our guesses as to composition variability indicate that if the radar altimeter data is unavailable the backscatter altimeter error will be less than $\pm$ 25%.

V. Conclusions

It has been found that the most suitable radiation system for low altitude measurement above the lunar surface is a gamma backscatter gauge. The required source strength ($\sim$12 curies) is practically achievable, and is easily shielded, provided that the gamma energy is not too high. Americium-241, 59.6 kev gamma emitter, appears to be an excellent choice of source. The detector might possibly be a scintillation device employing a ruggedized low noise multiplier photo tube. Because of the high counting rates it is probably more practical to measure the anode current than to use pulse counting techniques. The combined source and detector package could weigh about five pounds. The detector unit might require about five watts of power.

It is estimated that altitude error due to lunar surface composition variation might be of the order of $\pm$ 25%. However, single scatter theory shows that the composition and geometry dependent terms are separable so that if altitude is derived from the ratio of response at any altitude to the response at a known starting altitude, composition effects will cancel out. If a known starting altitude is provided at 50 ft by conventional low altitude radar (which has an accuracy of $\pm$ 1 ft) the gamma backscatter gauge will then meet the accuracy specifications supplied by MSC.

The effects of multiple scatter will have to be examined closely from the experimental point of view to see whether the cancellation is still adequate. Since the outlook is promising, a follow-up program is recommended.

VI. Recommendations

Since the study indicat ed that the gamma backscatter system offers many advantages as compared to other possible approaches, it is recommended that this system be examined in greater detail, both theoretically and experimentally. This effort should be directed towards determining those factors necessary to arrive at optimum design features, and to provide a thorough evaluation of the method. The program should not only provide this necessary information, but also an experimental model incorporating the basic design features indicated by the study.

Specifically areas of study should include:

(1) Variation of reflection coefficient with composition, and with manner of sampling the scattered spectrum. Selection of part of the scattered spectrum via pulse height analysis, and filters at the detector would be considered.

(2) Data generated in (1) can be evaluated to determine the degree to which the multiple scatter component can be included in the measurement, and the optimum means of achieving composition independence can be selected.

(3) Candidate detectors should receive further study to determine optimum choice. In particular, the practicality of a high pressure ionization chamber should be examined, and the question of anode current measurement vs. counting techniques should be resolved for the scintillation detector. In addition solid state detectors operated in the d.c. mode (as ionization current devices) should be considered.

(4) Further information should be extracted from possible source suppliers on the best means of fabricating the Am-241 source. Basic data on source self-absorption would be desired.

(5) An effort should be made to specify the most appropriate approach to the problem of electronic derivation of altitude from response data. This will depend upon the detector selected.

(6) The effect on accuracy caused by variation of detector operating conditions should be studied with the purposes of being able to establish specifications such as required high voltage stability, amplifier gain stability, etc.

(7) An experimental model using the selected detector, but employing laboratory electronics (except as otherwise convenient) should be constructed and tested. The source strength may be scaled down to a convenient level.

It is anticipated that a considerable amount of experimental work may be required in a low pressure (vacuum) chamber, due to the fact that experiments in the normal atmosphere will give unwanted effects from air scatter and attenuation. In the case of vacuum chamber experiments, wall scattering is a problem. Experiments will be planned such as to keep the extrapolation to real geometry (infinite plane surface and boundless vacuum) as accurate as possible.

FIG. 1

ASSUMED GAS DENSITY PROFILE FOR EXHAUST

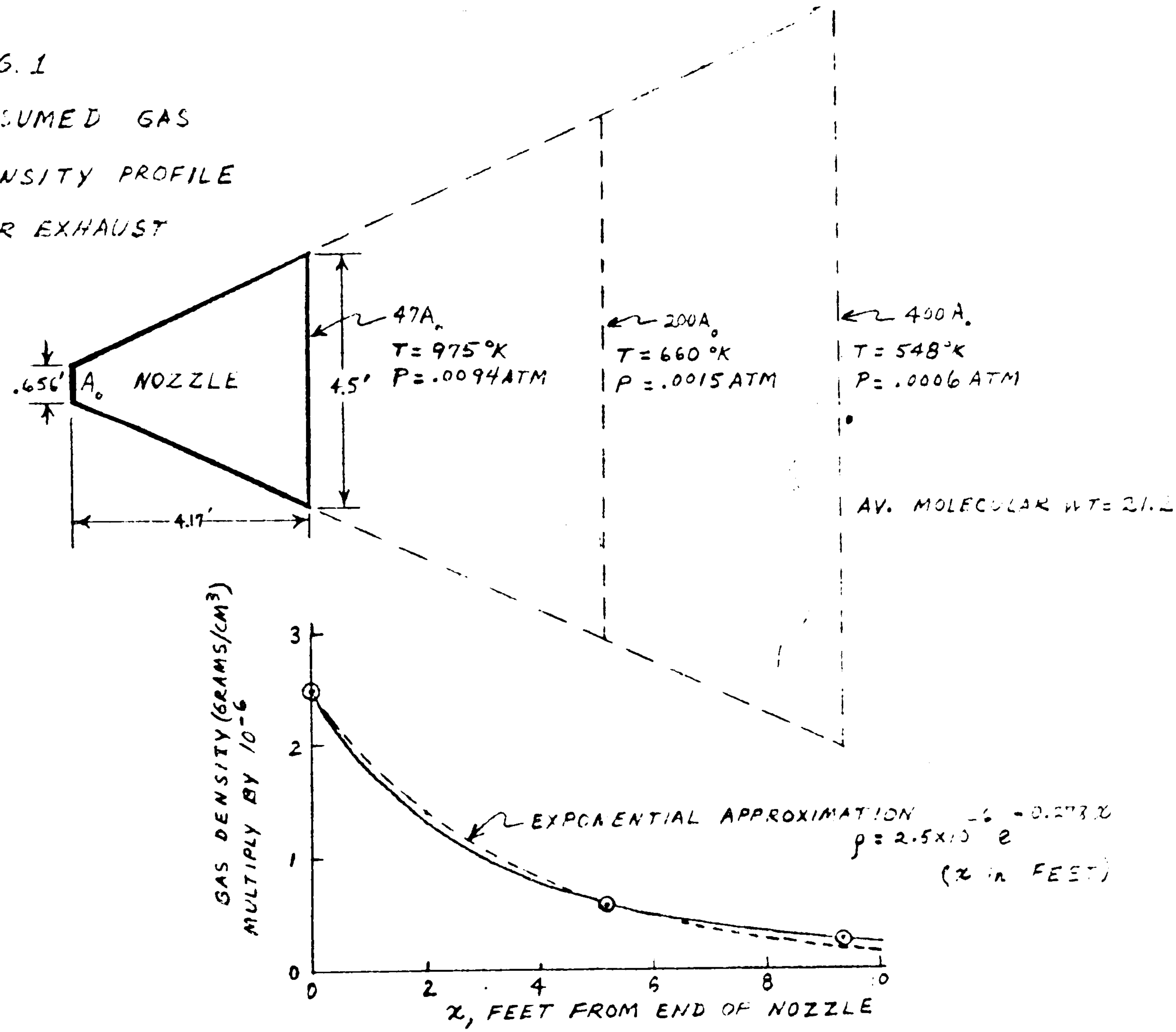


FIG. 2

REFERENCE FRAME FOR

BACKSCATTER CALCULATION

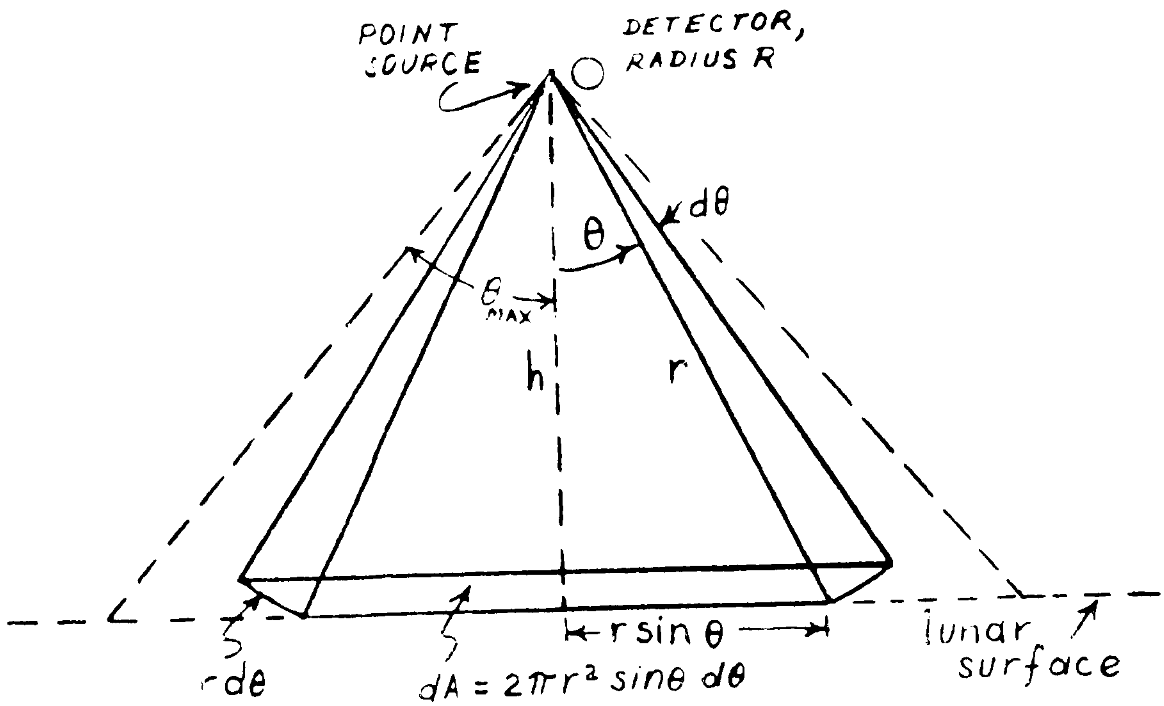


FIG. 3
THE INFLUENCE OF
IRRADIATION FIELD ON
RESPONSE

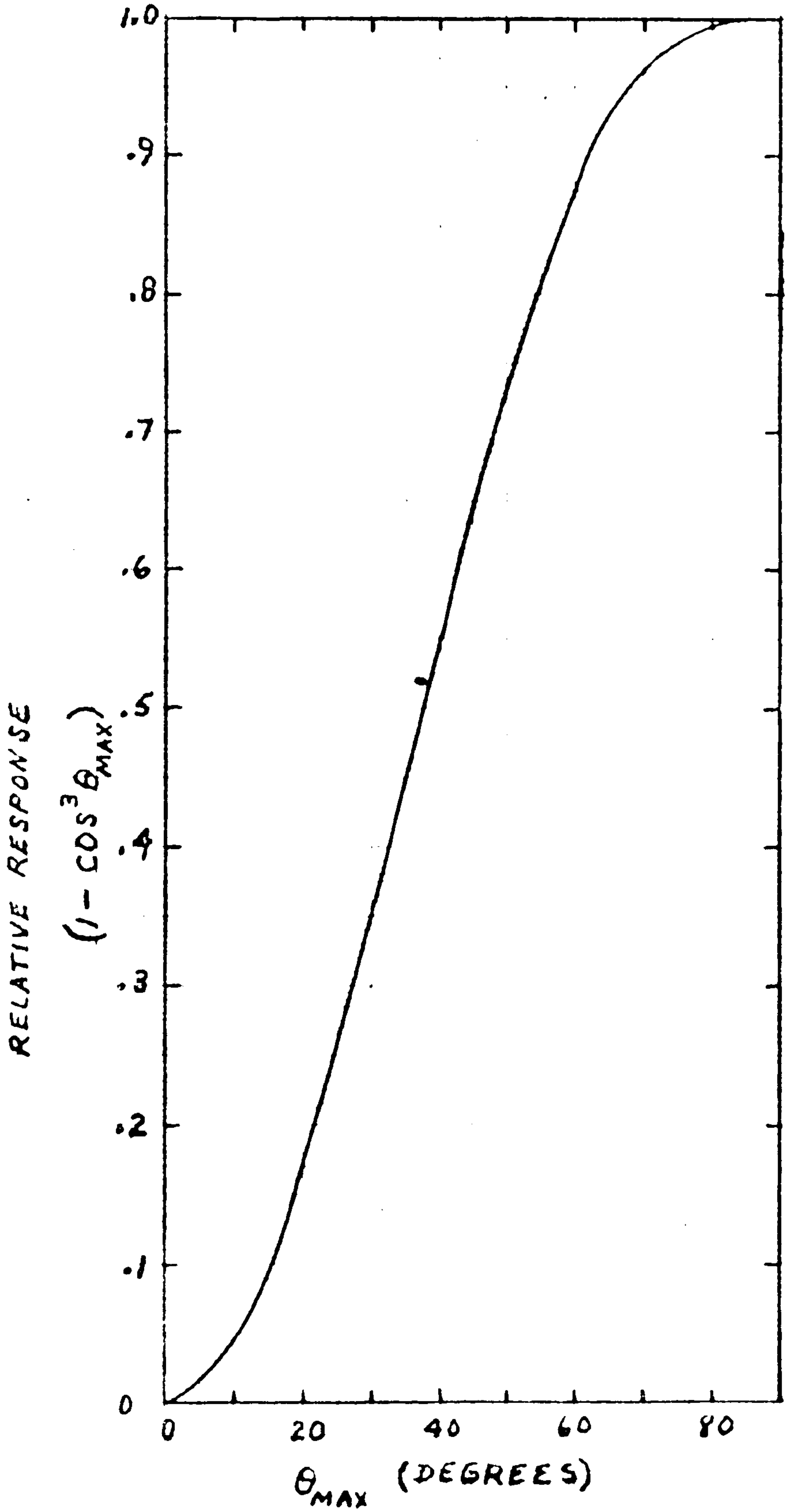


FIG. 4
EFFECTIVE RADIUS
OF IRRADIATION
FIELD AT LUNAR
SURFACE

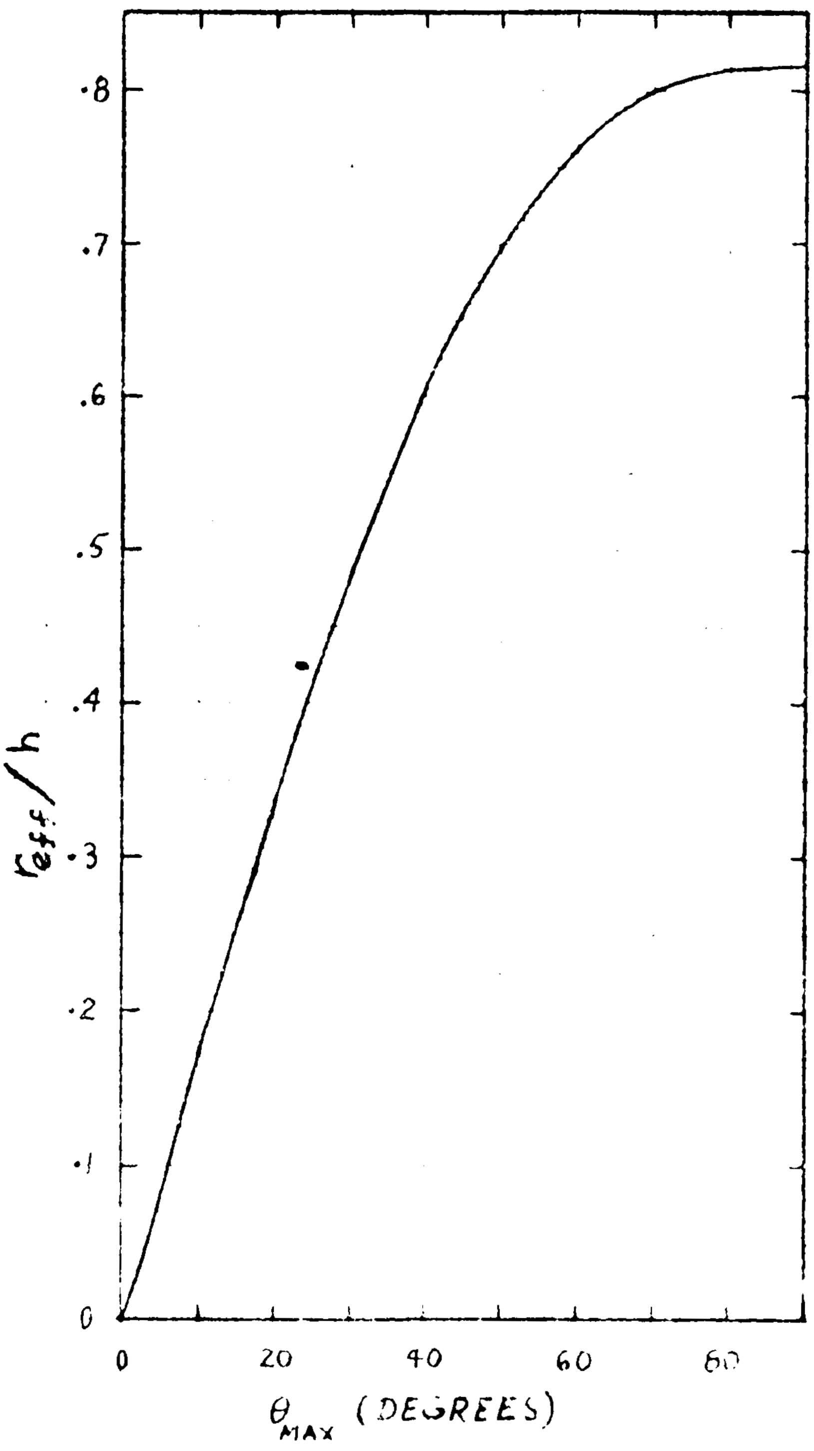
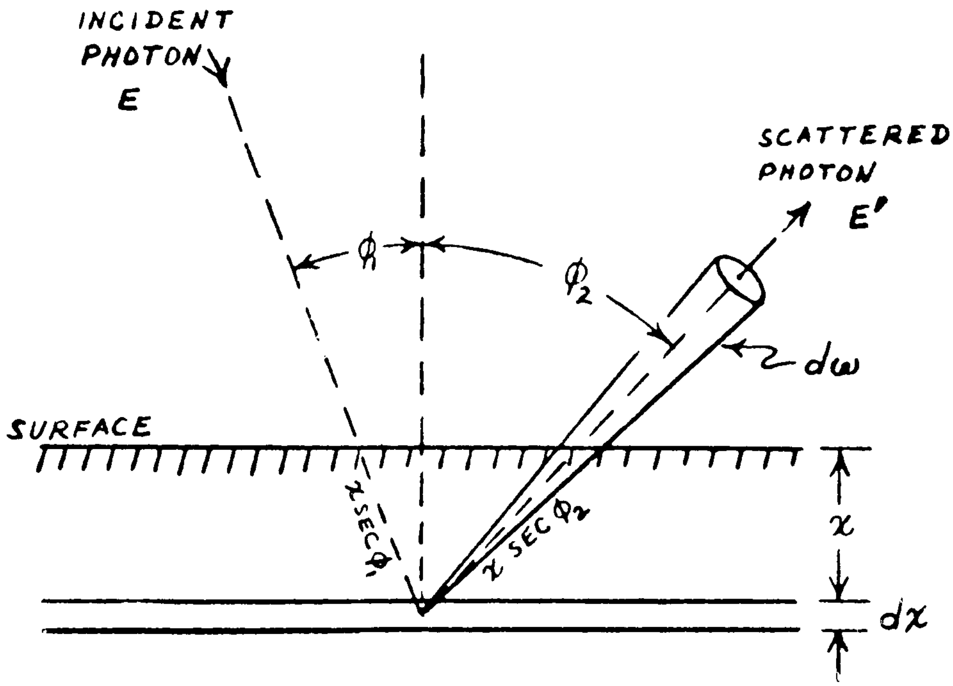


FIG. 5

REFERENCE FRAME FOR CALCULATING REFLECTION COEFFICIENT



SCATTERING ANGLE $= \theta = \pi - (\phi_1 + \phi_2)$

FIG. 6

ENERGY OF SCATTERED PHOTON FOR AN ANGLE OF 180°

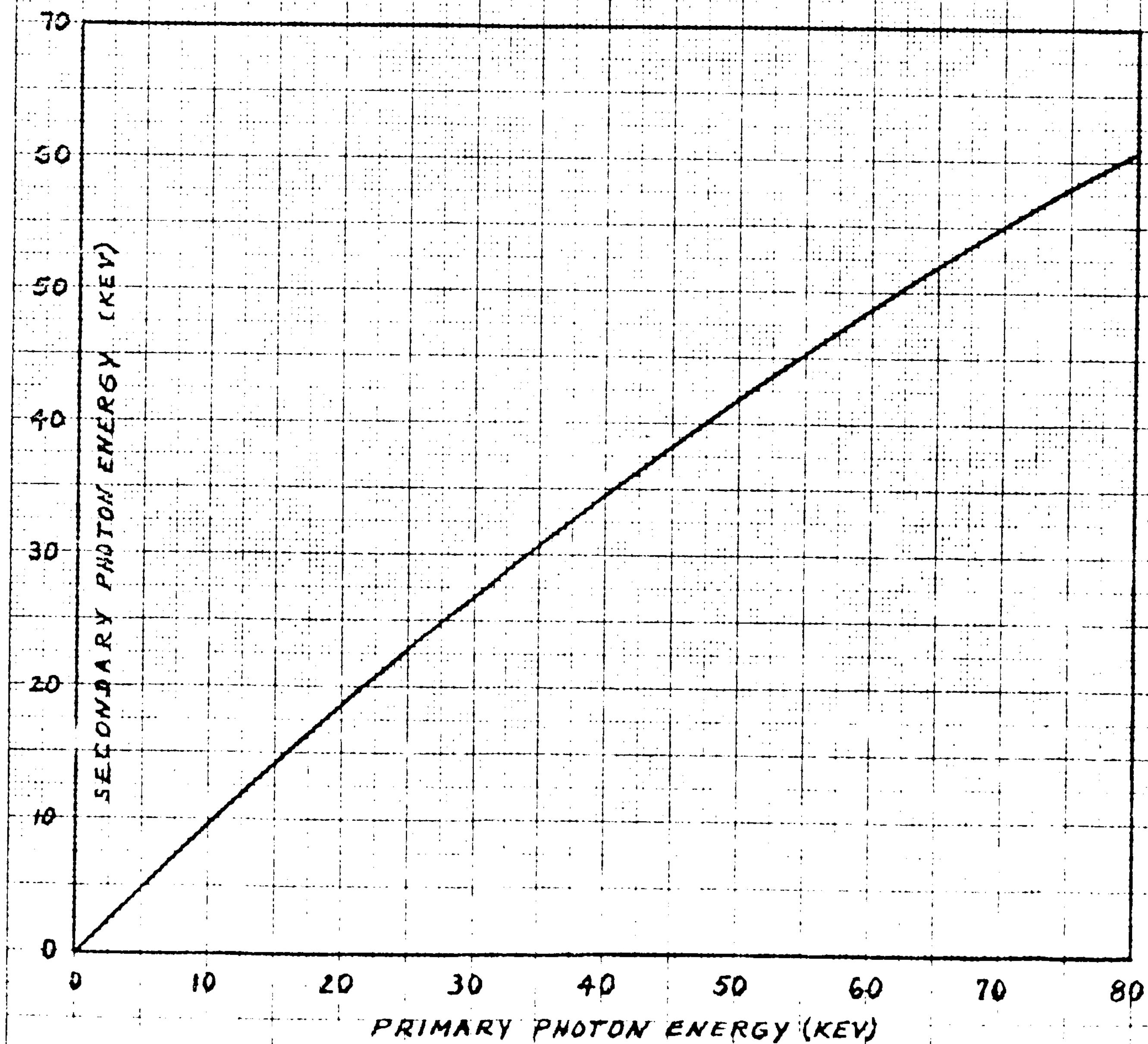
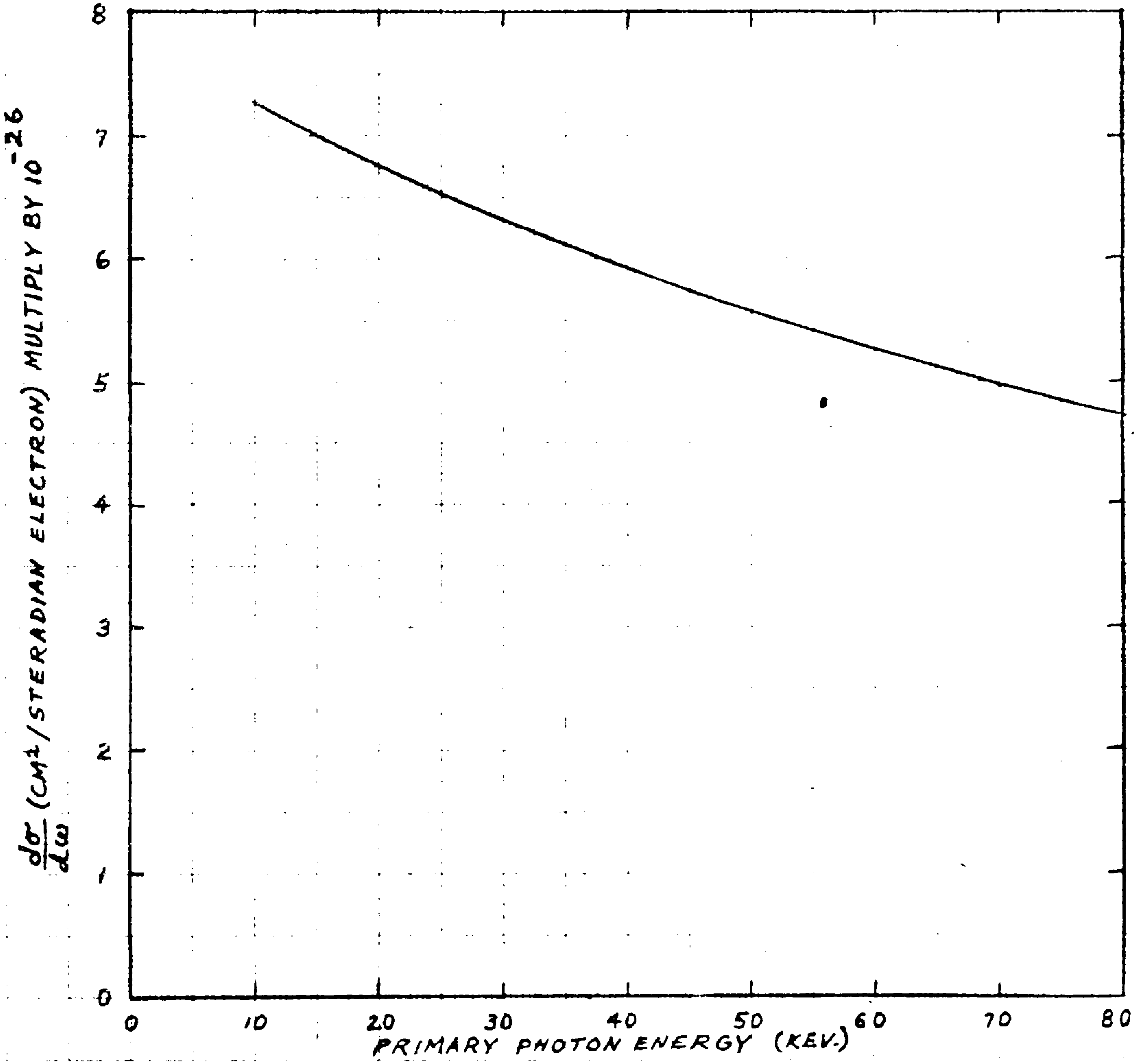


FIG. 7 COMPTON CROSS SECTION FOR 180°



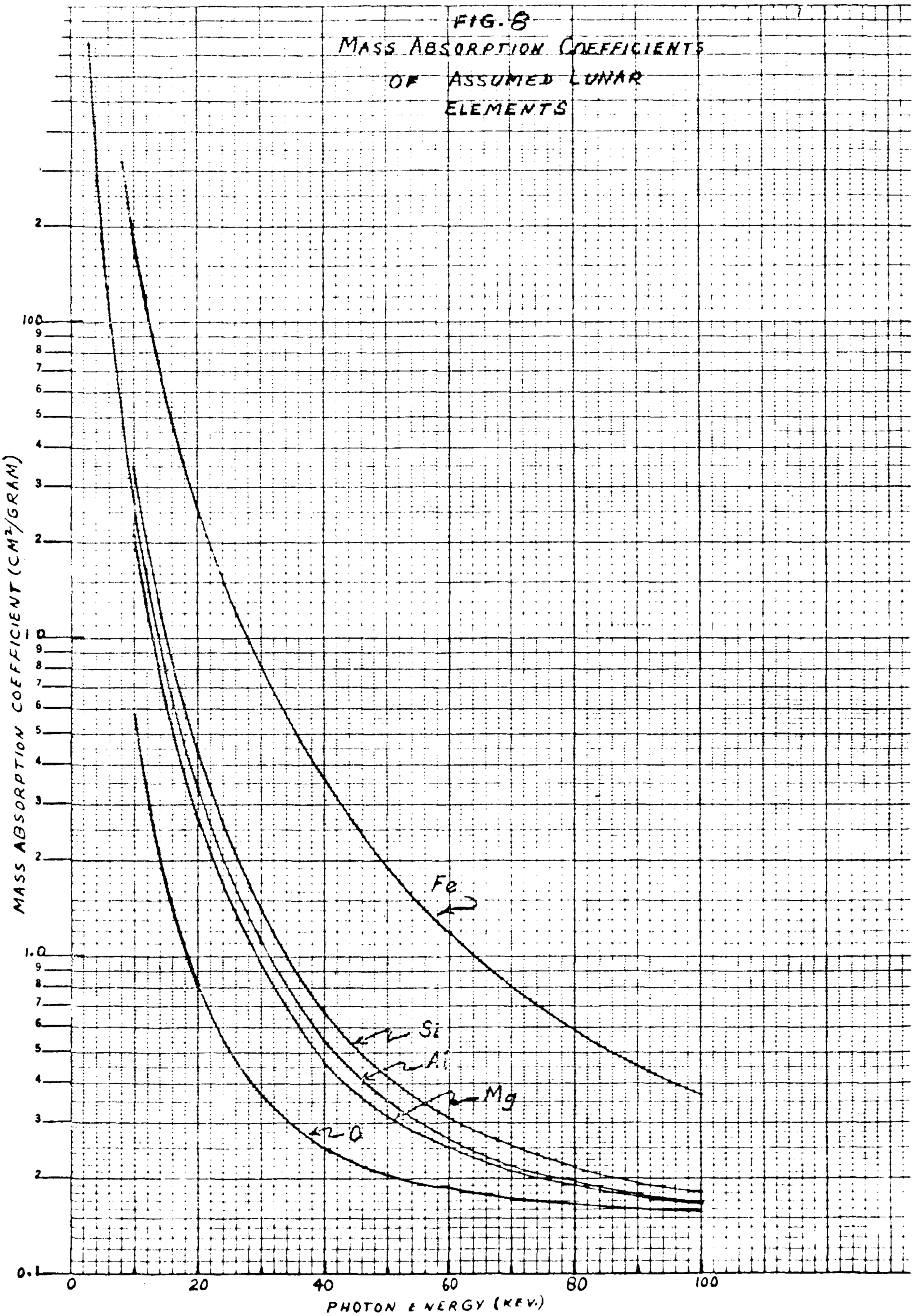
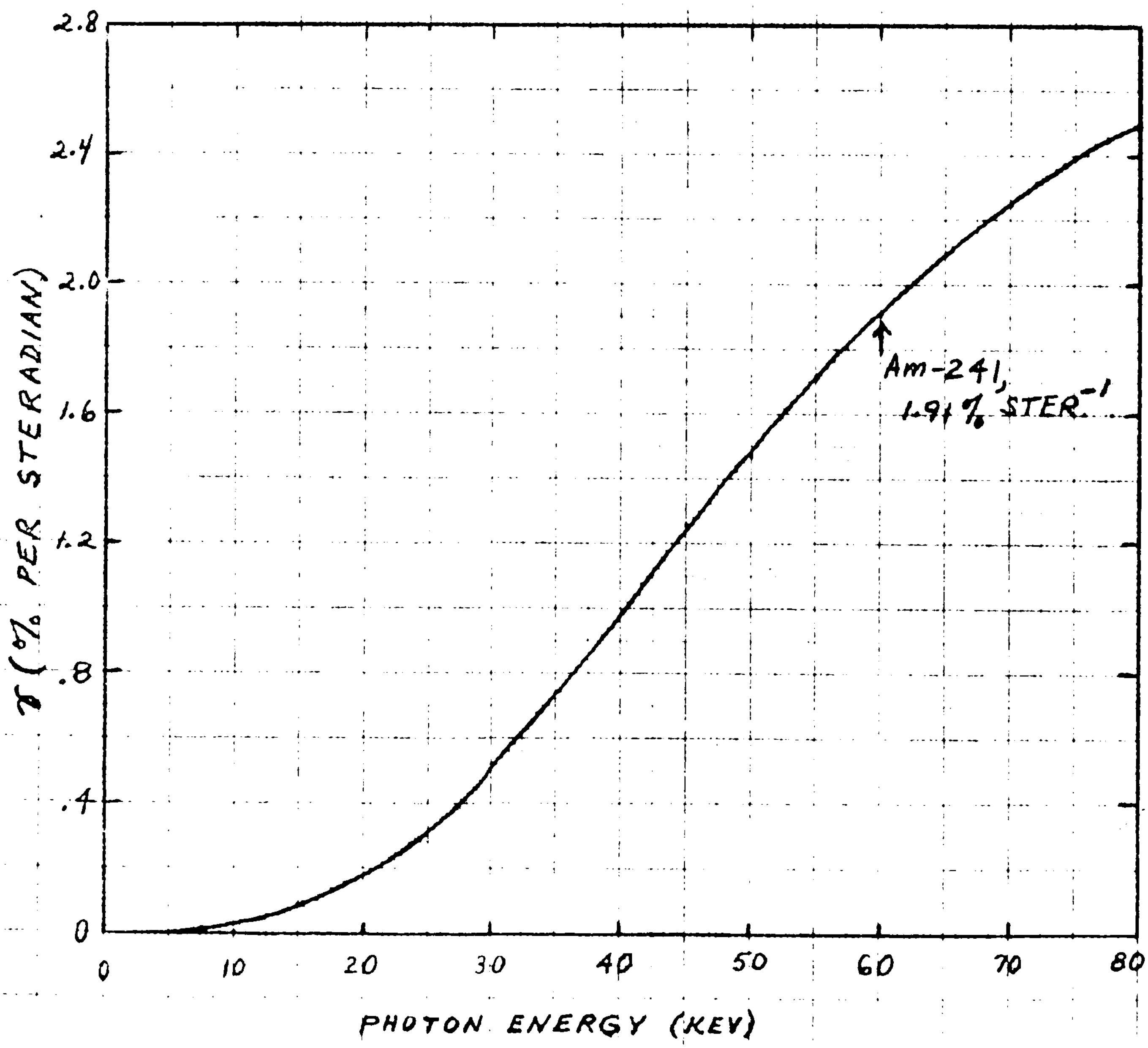
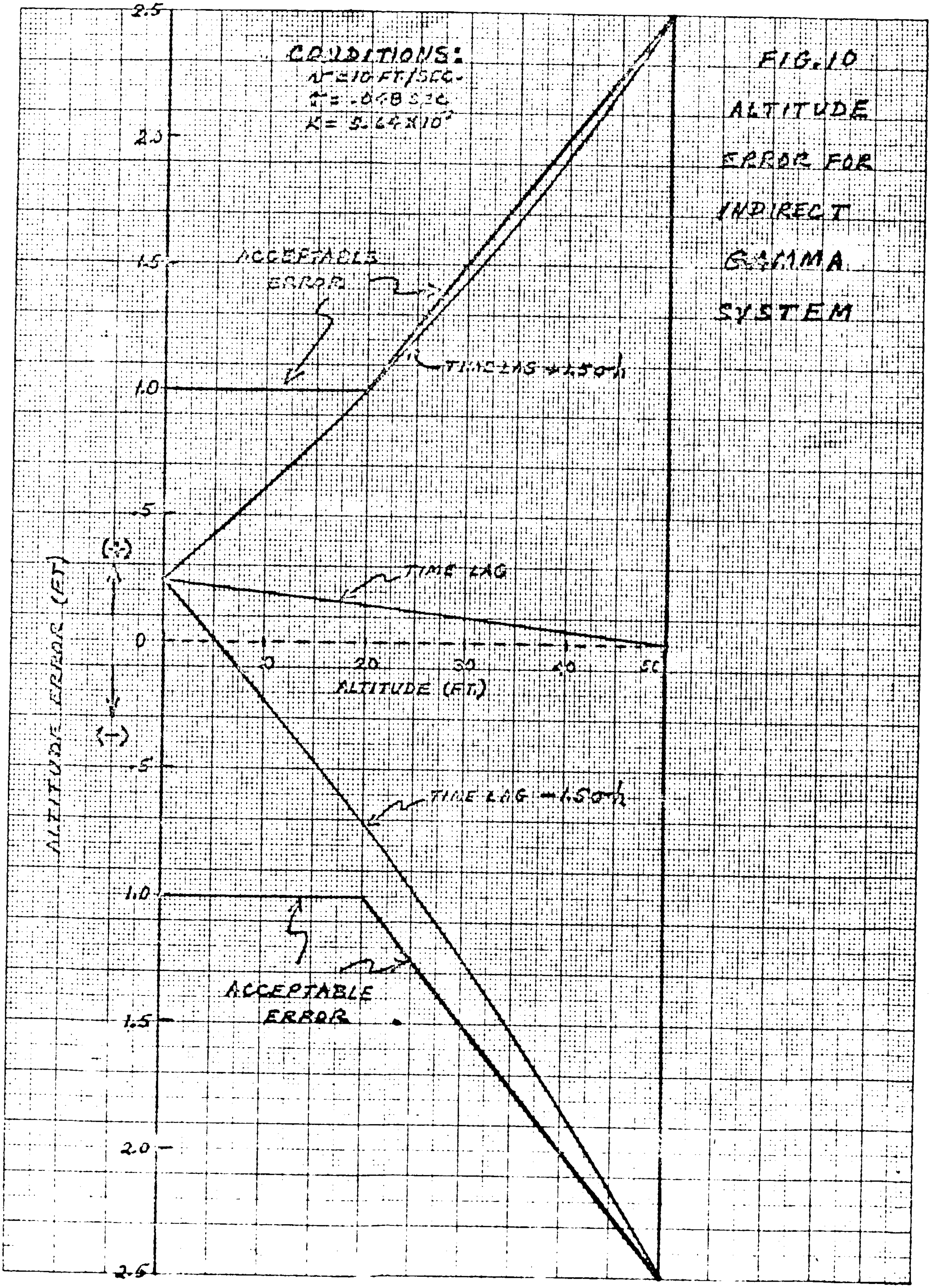


FIG. 8
MASS ABSORPTION COEFFICIENTS
OF ASSUMED LUNAR
ELEMENTS
Fe
Si
Al
Mg
O
MASS ABSORPTION COEFFICIENT (CM²/GRAM)
PHOTON ENERGY (KEV.)
100
10
1.0
0.1
0
20
40
60
80
100

FIG. 9

REFLECTION COEFFICIENT FOR ASSUMED LUNAR COMPOSITION AT $\theta = 180°$




CONDITIONS:
V = 10 FT/SEC
FIG. 10
ALTITUDE
ERROR FOR
INDIRECT
GAMMA
SYSTEM
ACCEPTABLE
ERROR
TIME LAG
TIME LAG
ACCEPTABLE
ERROR
ALTITUDE ERROR (FT)
ALTITUDE (FT.)
2.5
2.0
1.5
1.0
.5
0
.5
1.0
1.5
2.0
2.6
10
20
30
40
50
(+)
(−)

MODEL DATE

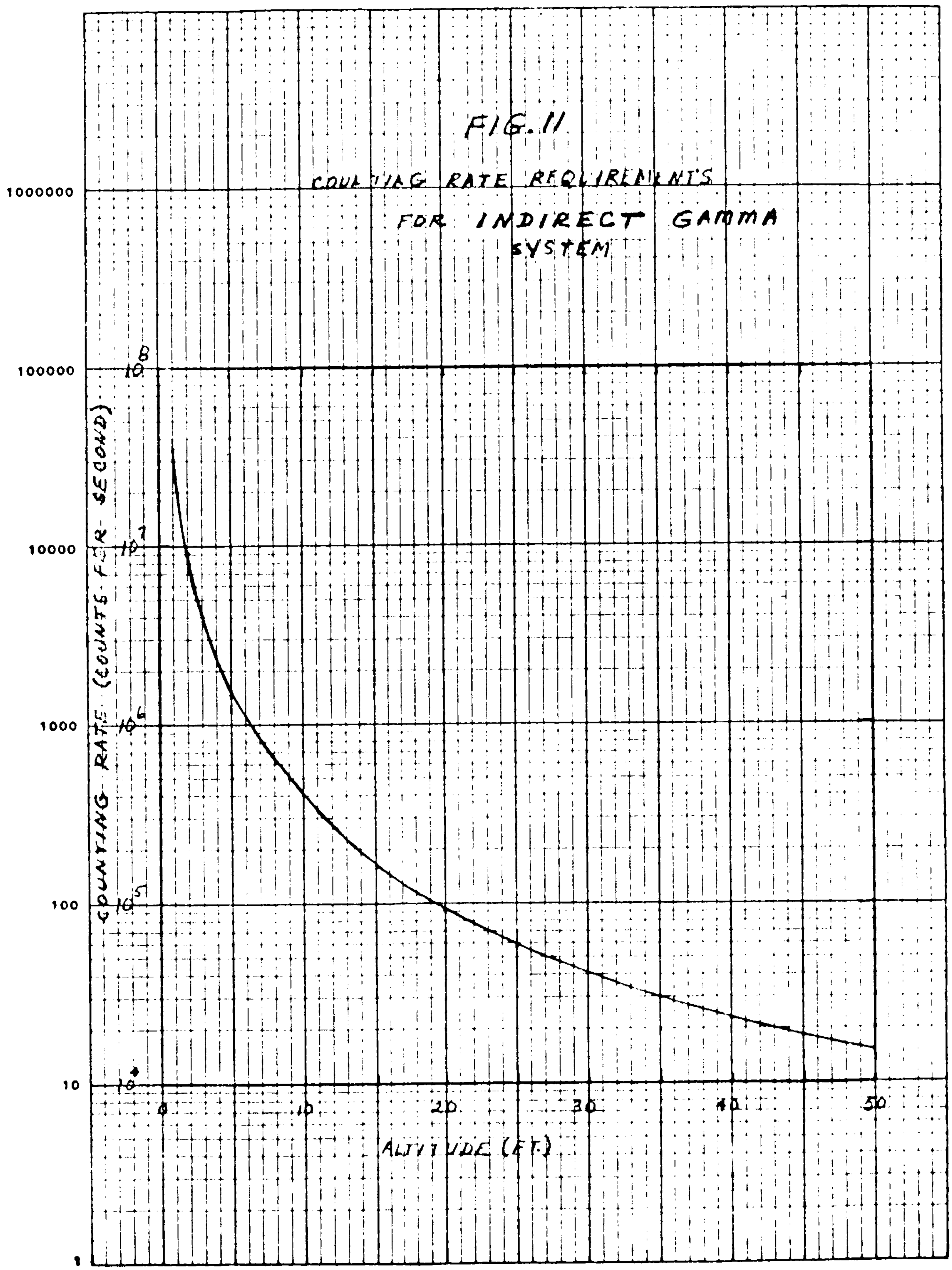


FIG. 11
COUNTING RATE REQUIREMENTS
FOR INDIRECT GAMMA SYSTEM
1000000
100000
10000
1000
100
10
1
10^8
10^7
10^6
10^5
10^4
COUNTING RATE (COUNTS PER SECOND)
0
10
20
30
40
50
ALTITUDE (FT.)

FIG. 12

TOLERABLE DUST CLOUD DENSITY
FOR GAMMA BACKSCATTER
SYSTEM ASSUMING
UNIFORM DENSITY PROFILE

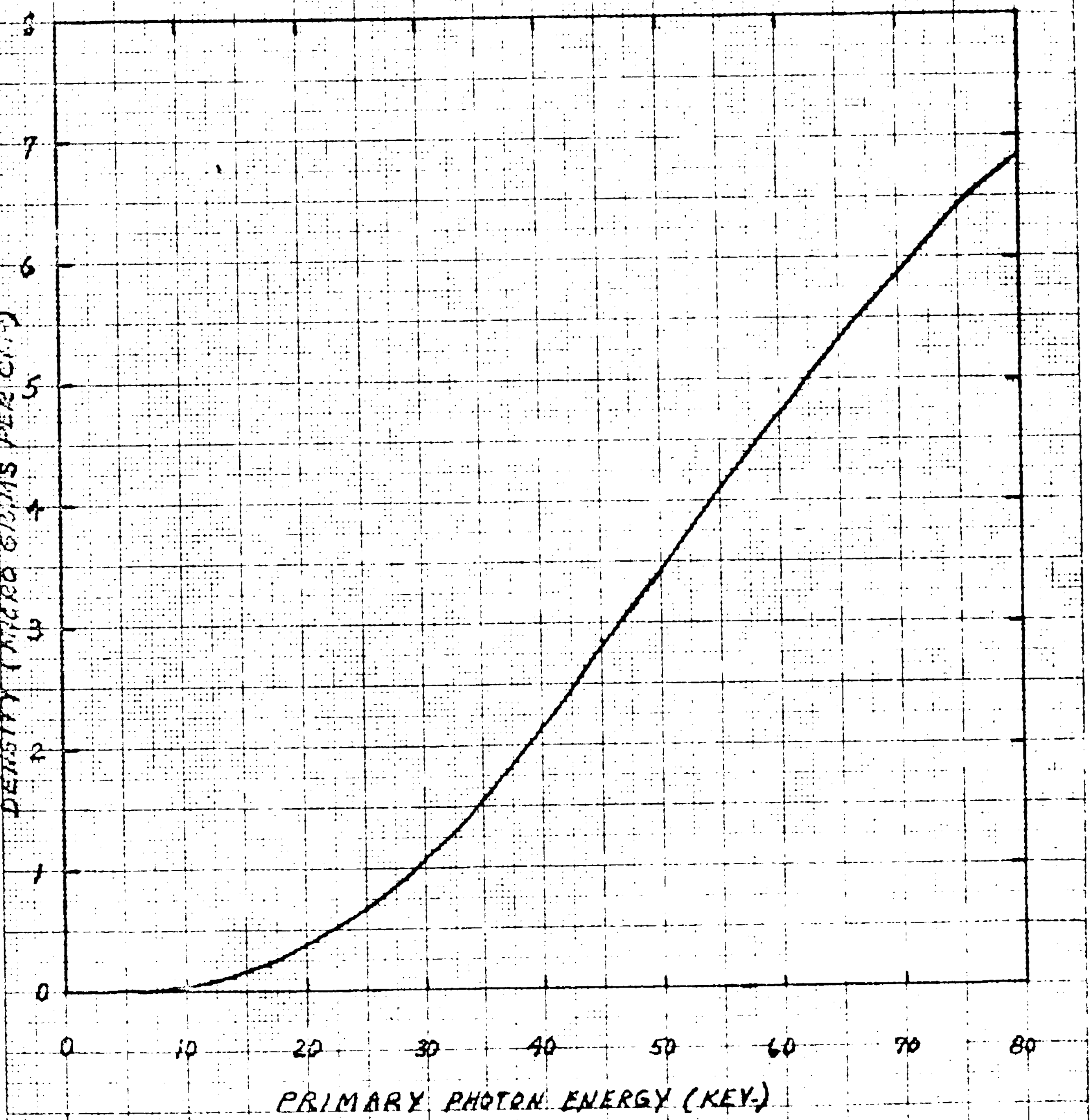


FIG. 13

CALCULATED EFFICIENCY DISTRIBUTION

FOR 4MM THICK NaI(TL) CRYSTAL

WITH 0.2 MM ALUMINUM WINDOW

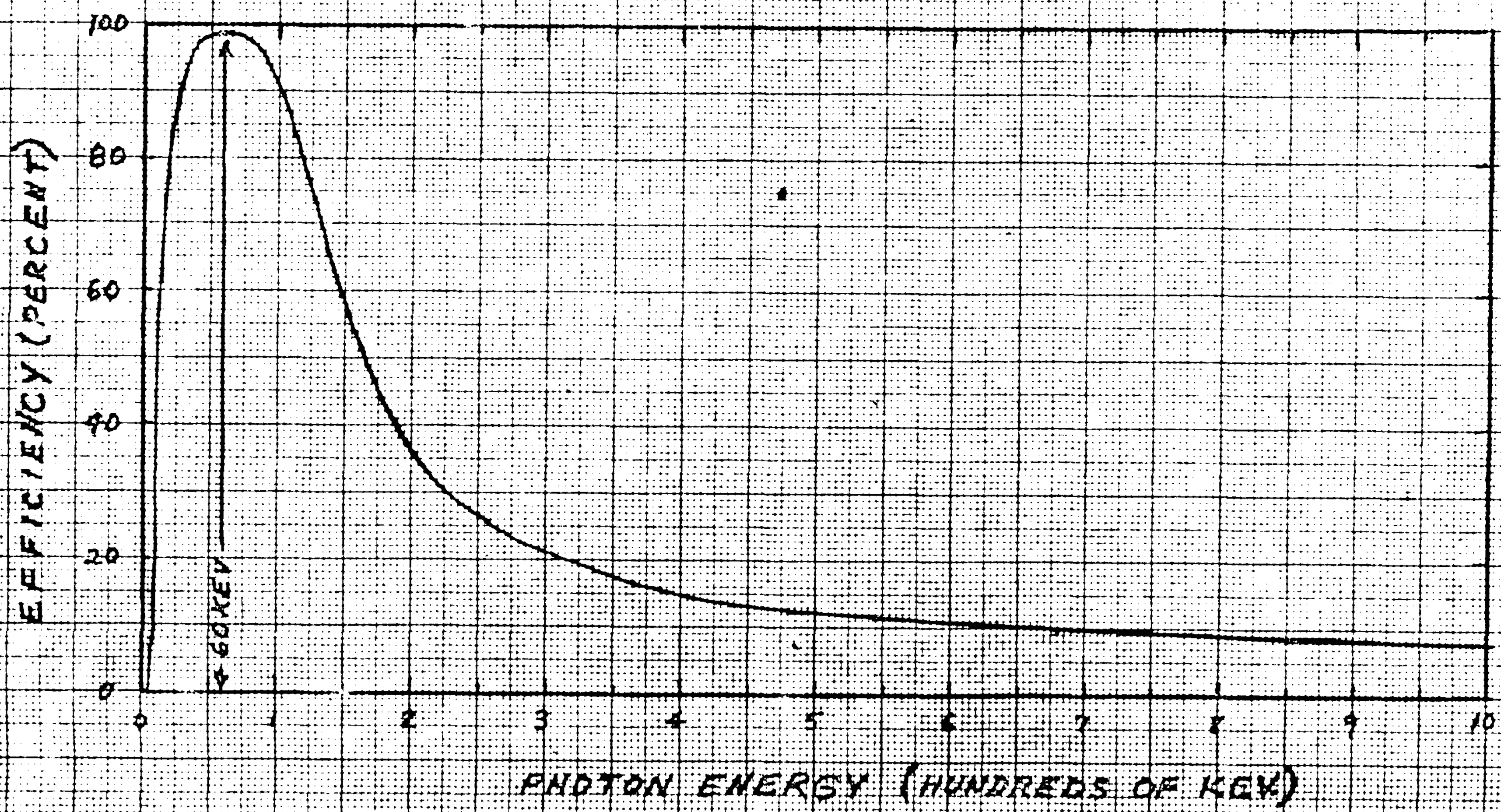


FIG. 14

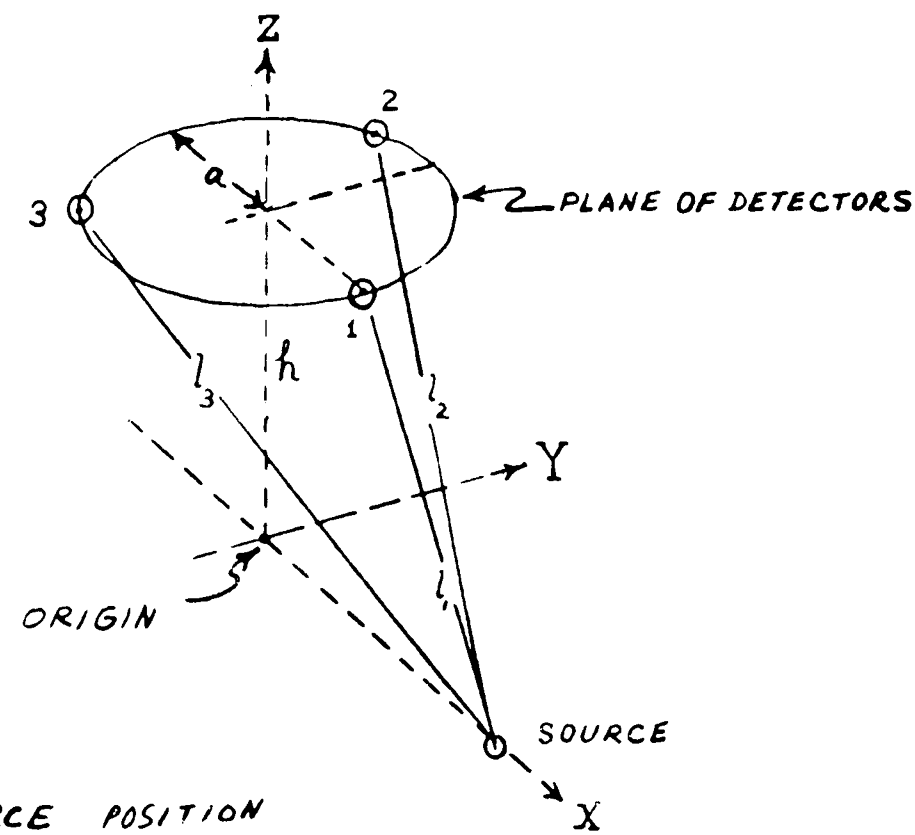
REFERENCE DIAGRAM FOR INDIRECT SYSTEM ANALYSIS

X-Y PLANE IS LUNAR SURFACE

DETECTOR #1 COORDINATES ARE x_1, y_1, h

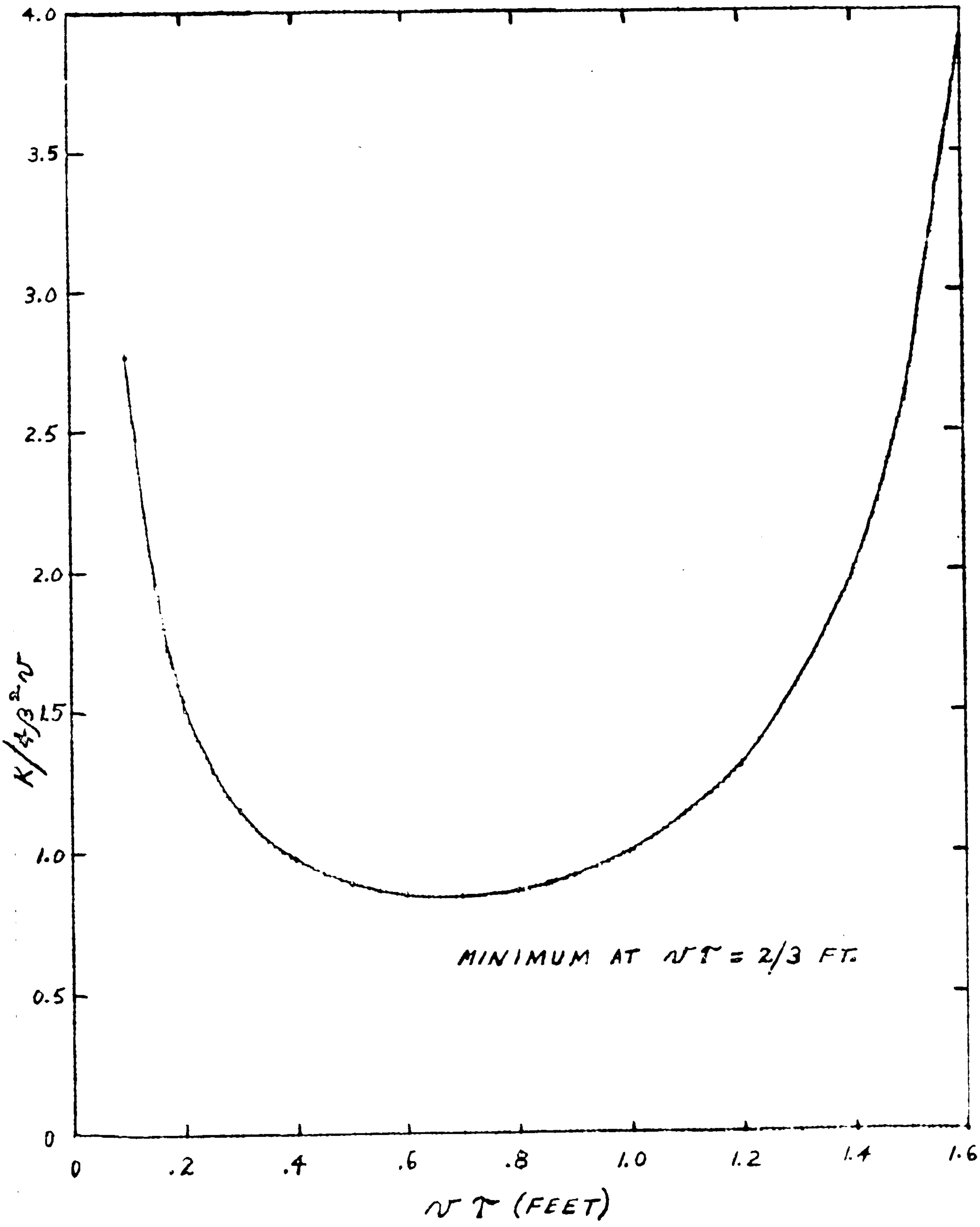
" #2 " " x_2, y_2, h

" #3 " " x_3, y_3, h



SOURCE POSITION
(a, 0, 0)

FIG. 15
RELATIVE SOURCE STRENGTH
REQUIREMENT FOR DIRECT
SYSTEM



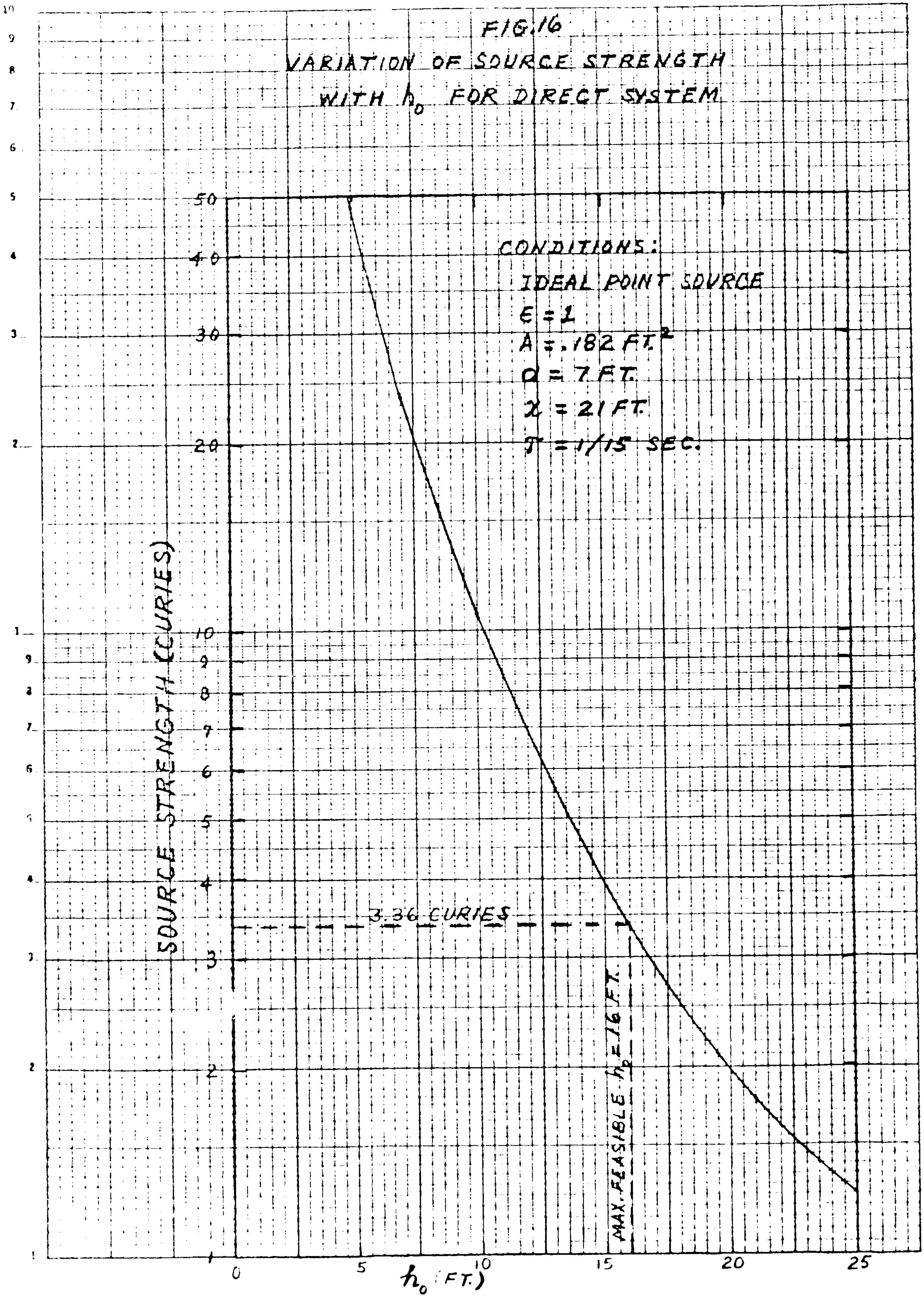


FIG. 16
VARIATION OF SOURCE STRENGTH
WITH h_0 FOR DIRECT SYSTEM
CONDITIONS:
IDEAL POINT SOURCE
E = 1
A = .182 FT.^{2}
a = 7 FT.
x = 21 FT.
T = 1/15 SEC.
SOURCE STRENGTH (CURIES)
3.36 CURIES
MAX. FEASIBLE h_0 = 16 FT.
h_0 (FT.)
0
5
10
15
20
25
50
40
30
20
10
9
8
7
6
5
4
3
2

FIG. 17

DETECTOR RESPONSE FOR DIRECT SYSTEM

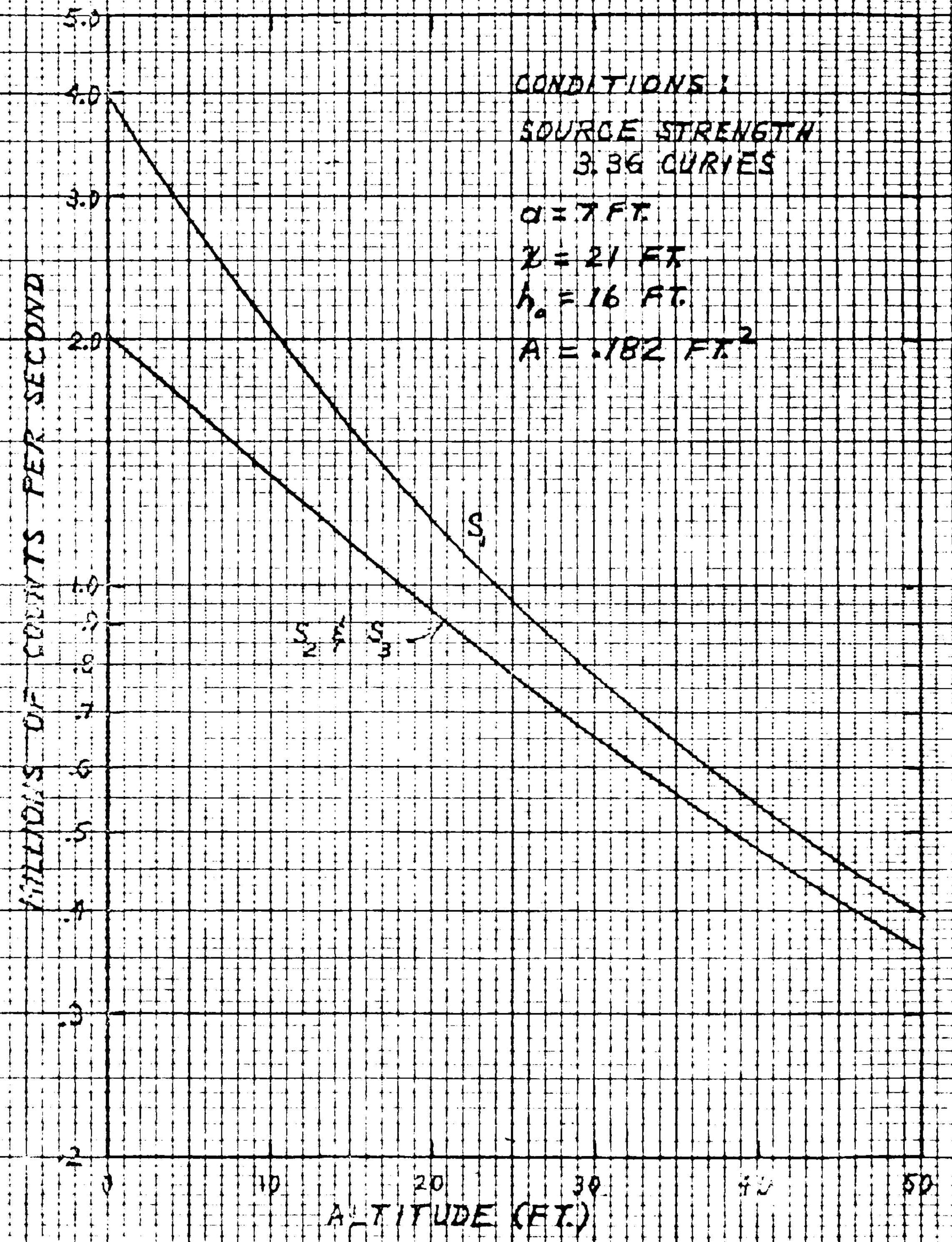


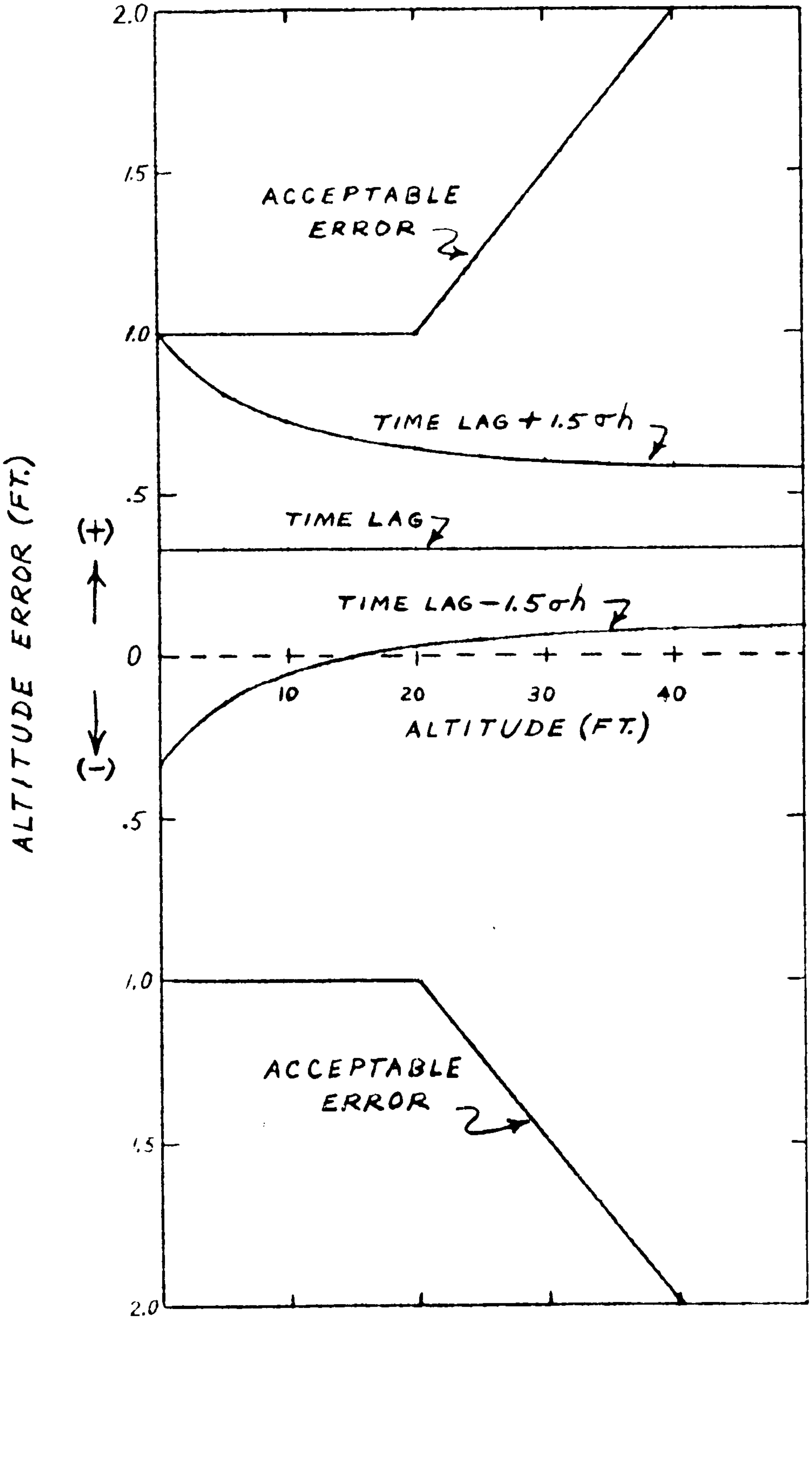
FIG. 1B

ALTITUDE ERROR FOR DIRECT SYSTEM

v = 10 FT./SEC.

τ = 1/15 SEC.

K = 1.8×10^9 COUNTS $SEC.^{-1}$ $FT.^{2}$



APPENDIX

NEUTRON SYSTEM

One indirect method of altitude measurement not mentioned in the text, would be that of directing a neutron beam down to the surface and detecting the return radiation. The return radiation may consist of scattered neutrons, or induced emission of protons, alpha and beta particles, and gamma rays. Detection of the scattered neutrons is not favorable because of very low detector efficiencies for neutrons, while the low range of the charged particles in the lunar surface material would give rise to a poor return yield. The best approach is to measure the gamma production since the production cross sections are favorable, the gammas are relatively penetrating in the surface materials, and since very good gamma counting efficiencies are possible. A small amount of gamma rays are produced by direct n,γ reactions with target nuclei, but these cross sections are quite low for the elements of interest here ($\sim$.5 millibarn). Nearly all of the gamma rays would be the result of inelastic scattering events in which the product nucleus is left in an excited state, from which it decays by emission of one or more gamma rays.

Since the most abundant element in the lunar surface is undoubtedly oxygen, the primary neutron beam should be energetic enough cause production of gamma rays from this element. Gamma energies which have been observed are 6.1, 6.9, and 7.1 mev. The threshold energy for production is slightly larger than the gamma energy so that a neutron energy greater than 7.5 mėv is desired. A good choice would be the 10 to 15 mev range. Aluminum in the surface material will produce gamma energies of .847, 1.025, and 2.23 mev. Gamma energy from magnesium will be 1.4 mev, and for iron about .85 mev. Data for silicon was not found but gamma energies would be expected to be in the same range as those for aluminum.

An estimate of the gamma return may be made if the total absorption cross section for neutrons and the gamma production cross sections are known. For the elements and neutron energy of interest (10 to 15 mev) total absorption cross sections are about 1.7 barns (1 barn = 10^{-24} cm^2), while gamma production cross sections for inelastic scattering are about .6 barns. We shall derive a "return coefficient" γ_n which may be compared with the reflection coefficient γ previously derived for gamma scattering. Absorption of the gamma rays in the surface material will not be taken into account. The calculation will then give an overestimate of γ_n.

Consider the case of normal incidence on the surface. The probability that an incident particle will reach a differential layer located beneath the surface a distance x is $\exp(-N\sigma_T x)$ where N is the number of nuclei per unit volume, and σ_T is total absorption cross section. The probability that a gamma ray will be produced in the differential layer of thickness dx is $N\sigma_\gamma\,dx$ where σ_γ is the cross section for production of gamma rays by inelastic scattering. These gamma rays are emitted in all directions so that the probability of gamma production in the differential layer per unit solid angle is $(1/4\pi) N\sigma_\gamma dx$. The combined result of all layers is

$$\gamma_n = \frac{1}{4\pi} N\sigma_\gamma \int_0^\infty (\exp - N\sigma_T x)dx = \frac{\sigma_\gamma}{4\pi\sigma_T} \text{ steradian}^{-1}$$

Using $\sigma_\gamma = .6$ barns and $\sigma_T = 1.7$ barns it is found that $\gamma_n = .028$ steradian^{-1} or 2.8% per steradian. This may be compared to a reflection coefficient of 1.9% for 60 kev gamma rays. Since γ_n is an overestimate, it appears that the two coefficients are approximately equal. Consequently, for equal detector efficiencies (to be discussed subsequently) a neutron source of about the same strength as the Am-241 source is required, viz., 2.36 curies (ideal point source equivalent).

We now examine the question of providing an adequate neutron source. Radium-beryllium sources are the most commonly used because they are easily fabricated and have a long half life (~1600 years). Alpha particles from the decay of radium are used to bombard beryllium and the reaction

$$_4Be^9 + {}_2He^4 \longrightarrow {}_6C^{12} + {}_0n^1$$

occurs. However, the decay products of radium yield copious amounts of energetic gamma rays which would require heavy shielding. This source is, therefore, not a good choice. Since a much lower gamma ray emission is associated with a polonium-beryllium source, and since the neutron yield is only moderately less, this source would be more favorable. The half life is 138 days. This is not necessarily objectionable because the trip to the moon may take about 100 hours. The yield of conventional polonium-beryllium sources is about 1.8×10^6 neutrons/sec per curie of polonium. Since the number of neutrons/sec needed is $2.36 \times 3.7 \times 10^{10} = 8.73 \times 10^{10}$, the number of curies of polonium required is $8.73 \times 10^{10} / 1.8 \times 10^6 = 4.85 \times 10^4$. The source would, therefore, require 48,500 curies of polonium. Such a large source does not lie within the realm of practical achievement. The required neutron flux could only be supplied by an electrically operated neutron generator.

Generators may be classified in two categories, according to whether the particle beam used for bombardment is positively or negatively charged. The most usable positive particle reactions are:

$Be^9(d,n)B^{10}$:	usual bombarding energy 1 to 2 mev, neutron spectrum 0.5 to 6 mev.
$H^2(d,n)He^3$:	optimum bombarding energy .5 mev, neutron spectrum 10 to 16 mev.
$Li^7(p,n)Be^3$:	threshold at 1.9 mev, yield increases rapidly above threshold with increasing bombarding energy; neutron energy 1 mev at 2.5 mev bombarding energy and 3 mev at 5 mev bombarding energy.
$H^3(p,n)He^3$:	threshold at 1.2 mev, yield increases rapidly above threshold with increasing bombarding energy; neutron energy 0.7 mev at 1.5 mev bombarding energy and 3 mev at 4 mev bombarding energy.

Since a neutron energy of greater than 7.5 mev would be desirable, only the second reaction above would be useful. Yields for this reaction using a 2.5 mg/cm^2 thick Ti-H^3 target with 0.5 mev bombarding energy are about 10^8 neutrons/sec./μamp. Thus, to achieve the required ~10^{11} neutrons/sec. a 1 milliamp beam current would be required. At 0.5 mev the power supply would have to deliver 500 watts of power. Alternately if a .1 mev supply is used, where the yield is 10^7 neutrons/sec/μamp the beam current would have to be about 10 milliamps. The beam power would be 1 kw. However, targets which will withstand these power levels have not yet been developed.

The negative particle or electron bombardment devices use electrons to produce high energy x-ray bremsstrahlung. The x-rays in turn cause photodisintegration reactions with the target nuclei to yield neutrons. The most useful reactions are:

$Be^9(\gamma, n)Be^8$:	threshold energy - 1.66 mev
$H^2(\gamma, n)H^1$:	threshold energy - 2.2 mev
$U^{nat}(\gamma, n)U$:	threshold energy - 9 mev.
$U^{235}(\gamma, f)U$:	

Yields are highest for the $U(\gamma, f)$ reaction, being about 10^{11} neutrons/sec/μamp of beam current at an electron energy of 50 mev. Thus, 10^{11} neutrons/sec are produced with only 50 watts of power. The neutron spectrum peaks at 1 to 2 mev and is down to a few percent of peak value at 8 mev. Consequently, much of the spectrum would not be useful for gamma production at the lunar surface. In addition the large amounts of high energy x-rays produced would require very heavy shielding for the detector, and relatively heavy shielding for personnel.

While an appropriate (and adequate) selection of neutron generators would require further study, it can at least be said that such equipment would be very bulky and power consuming. This "machinery" can not even be compared with the 1-1/4 pound Am-241 source mount needed for the gamma backscatter system. It is furthermore true that the detector for the neutron system would have to be much heavier than for the 60 kev gamma system, since gamma ray photons of several mev must be detected.

The neutron method would, of course, be composition dependent. The technique suggested for the gamma backscatter system might be applied, but the composition cancellation should be less satisfactory since the high energy gamma rays will give rise to considerable multiple Compton scattering in the surface material.

It may be concluded that the neutron-gamma system would require a considerable amount of hardware, and is, therefore, very unattractive as a means for measuring altitude above the lunar surface.