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EFFECTS OF INTERFACES ON GAMMA SHIELDING

by

C.E. Clifford

(2, C) NSA

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The spatial distribution and the energy spectrum of scattered gamma rays in infinite homogeneous media have been determined for a wide range of initial gamma energies and scattering materials. In general the dose rates calculated from the published infinite medium buildup factors are confirmed in corresponding experiments (1). Because of the reliability of the results for infinite homogeneous media considerable attention has been given to the application of the infinite media data to shielding problems involving finite structures. The recent NBS monograph of Dr. Spencer (2) is an outstanding illustration of how the results of infinite medium calculations can be applied to the solution of many shielding problems. However there are problems in which boundary effects markedly alter the energy and number distributions of scattered γ radiation from those to be expected in an infinite medium.

Shielding problems involving interfaces or boundaries are frequently treated either by applying a correction factor to a corresponding infinite medium case or by using infinite medium results as far as the boundary or discontinuity and then applying a factor which depends only on the nature of the boundary. The bulk of the studies on boundary effects on gamma scattering can be grouped into three general categories as shown in the first slide (Fig. 1). Each of these categories will be discussed in turn. The object is to survey what has been done in order to give some perspective to what is being studied at present. In addition I propose to digress a couple of times in order to present the results of some recent work at DRCL. Since our concern is with shielding our interest is directed mainly to those interface scattering problems in which the detector is in air. It should perhaps be mentioned that with only a few exceptions experimental work has been confined to X-ray and γ energies below 2.8 Mev. Theoretical work however has frequently been extended to higher energies so that much of our information on the problem of high energy γ shielding, for example against the 6.13 Mev γ's from neutron capture in nitrogen, is based on theoretical work.

The first of the categories listed - dealing with sources at an interface - has received a great deal of attention and most of this attention has been concentrated on the particular case of contamination at the interface between air and ground or between materials with a correspondingly large density ratio. Since many shielding problems of this type are concerned with situations in which the bulk of the radiation received by a detector has been transmitted through the air along an air-ground boundary rather than through the ground, the object of many studies was to determine the extent to which the calculated dose distributions for an infinite air medium were modified by the presence of ground. To this end, the increase in dose due to backscatter was measured, using ionization chambers and scintillation techniques, as a function of the atomic number, the thickness and the area of the backscattering ground about a decade ago (3, 4, 5, 6). In 1957 Berger (7) published the results of a Monte Carlo study that presented air-ground correction factors to infinite medium calculations for the scattered dose to a detector at heights up to 1 mfp and radial distances of 4 mfp for a source at a density interface both for perfectly absorbing ground and for a ground which had the same scattering properties per gram as the region above it. Except at close-in distances good agreement with these calculations has since been observed by several investigators using Co^{60} and Cs^{137} γ sources at interfaces of air-clay, air-concrete, air-lead, polystyrene-concrete and steel wool on steel (8, 9, 10). At the close-in positions where the bulk of the observed dose is due to primary or unscattered radiation rather than to scattered radiation the accuracy of the calculated values is less and discrepancies between observed and calculated values were noticed. However the effect on shielding protection factors is not large since the dose due to primary radiation is the dominant component in this region. Further confirmation of Berger's calculations have been shown in measurements made with Co^{60} and a detector in water for grounds of Al, Ni, air and Pb (11). In all cases the interface corrections were within the limits for the 2 types of grounds considered by Berger. The effects of uniform contamination at an air ground interface on dose and energy distributions have been studied by several techniques including measurements in actual fallout fields and the use of various scaling systems. More commonly, contamination fields are simulated by using point isotropic sources and repeating measurements with different source locations until with the aid of symmetry an entire field may be mapped. With a single source this is a tedious procedure although the result is the detailed dose, energy or number contribution from any portion of the contaminated region. In recent years the development of the pumped source (12) in which a point isotropic source is moved through a flexible tube at a fixed rate over a predetermined portion of a field has greatly speeded the evaluation of the shielding provided by a given structure and hence the reliability of the assumptions about barrier shielding that are made in corresponding calculations.

For uniform contamination at an interface the radiation backscattered from the sky, commonly called skyshine, is of particular interest in fallout protection studies. Comparisons between observed values with Cs^{137} contamination and those obtained from infinite medium calculations of the backscattered dose from a plane source in an infinite homogeneous medium have shown good agreement (9). Another feature of interest is the extent to which the scattered radiation from a denser medium emerges at a distance from a source of primary radiation. At a recent ANS meeting Davisson and Beach (13) presented some results of a Monte Carlo study that included this feature and reported qualitative agreement with the experiments of others (14, 15). It might appear therefore that the behaviour of γ radiation from a source or sources at interfaces is well understood. Unfortunately there are still problems to which at best we have only qualitative answers. One of these is the effect of interface roughness. Clearly if a contaminated ground is rough it can absorb some primary radiation that would otherwise have reached a detector that is close to the rough ground. As the detector is moved away from the ground this effect will be reduced but a troublesome shielding problem is evident when it is required to relate the particular dose observed over such a region, for example in reconnaissance aircraft, to the corresponding dose to a person on the ground. If ground roughness had no effect, then the required calibration factor would follow directly from the dose vs height variation above a smooth contaminated surface. This variation is shown in the next slide (Fig. 2) for several different calculations (2, 16, 17) for an isotropic detector. As you see they are in reasonable agreement to a height of 150 meters or so where they indicate a calibrating factor of about 10 to give the dose near the ground. Incidently there are very few available experimental checks on these curves although later this morning we shall hear about an experiment in which the dose was measured to a height of nearly 150 meters for both Co^{60} and Cs^{137} sources. In practice, a collimated detector would probably be required in an aircraft surveying a contaminated region in order to eliminate the effects of distant hot spots and this would have the effect of increasing the calibration factor. With a half angle of 45° at the detector the corresponding correction factor at a height of 150 meters would become about 25 (2). This means that the dose at ground level would be assumed to be 25 times that observed in the aircraft. Various schemes have been proposed to allow for the possible effect of ground roughness on the dose predicted on the basis of this factor for a smooth plane. Some of these are shown in the next slide (Fig. 3).

These proposals range from ignoring ground roughness which would give an upper limit to the actual dose at ground level to considering the ground to be so rough that no direct radiation could reach a detector at a height of 1 meter. In this case the actual dose would approximate the skyshine component of the total dose above a smooth plane. In between we have various empirical factors (18, 19) and proposals to consider ground roughness as equivalent to raising the detector or to mixing the contamination with a given amount of soil or to consider it as buried beneath a thin layer of soil (20, 21). In each of these proposed cases the resultant decrease in the dose is considered to be representative of the decrease produced by surface roughness and can be calculated.

Clearly, there is a wide range of possibilities. Unfortunately there are only a limited number of measurements and what is required is more evidence of what values are probable for a variety of conditions. Later this morning we shall hear of a measurement of ground roughness in an actual fallout field. I would now like to digress briefly to describe a recent experimental check (22) at DRCL involving a simulated rough field. As described in the Transactions the dose was measured for various distributions of Cs^{137} on fields of concrete slabs arranged to simulate a concrete ground with a sawtooth profile of 6" depth as shown on the next slide (Fig. 4). Dose measurements were made for various detector heights and point source distances for different source locations on the slabs. The flat slab position 5 was included for comparison with earlier measurements on flat clay fields. Two types of fields were considered, a rectangular field similar to a ploughed field, and a concentric field which is a field in which the sawtooth profiles were everywhere at right angles to the source to detector line. For a detector height of 1 meter source to detector distances varied to 100 meters and it was possible to extend the results to 400 meters by comparison with earlier flat field measurements. For both fields we obtained the integrated dose at height 1 meter for fields that had the same density of contamination on the horizontal projection of their sawtooth profiles. The resulting ratios for the dose with a rough field to the dose for a smooth field are listed in the Transactions for a detector height of 1 meter and it is apparent that even moderate roughness could upset the smooth field calculations and observations by a factor of 2 or more. For the extreme case of the concentric field the effect of the detector height on the rough to smooth field ratio is shown in the next slide (Fig. 5) for a field contaminated to 70 meters radius. This shows how the effect of the ground roughness on the dose decreases with increasing height and that near the ground the value of dose reduction depends greatly on the particular assumed distribution of contamination. Lack of knowledge of ground roughness effects is probably the largest source of error in determining the dose with height above a contaminated plane and until we have some method of calculating it accurately, we can't altogether be happy with our knowledge of the behaviour of radiation for sources at an interface.

The next general category of work concerns the backscatter of radiation from an interface. In many shielding problems the primary radiation from a source is largely prevented from reaching a detector so that the radiation hazard may be due entirely to radiation scattered from walls down a passageway or service duct. The amount, energies and directions of the radiation scattered is then of great importance. Early experiments established that the amount of radiation backscattered and the corresponding dose depended markedly on the energy and angle of incidence of the incident radiation and on the atomic number of the backscattering material. In 1950 the results were published of calculations on the backscattered dose produced by radiation normally incident on a pure Compton scatterer using a first order approximation to the transport equation (23). Soon thereafter the Monte Carlo technique was applied to backscattering problems and by 1957 had been used to calculate the numbers, energies and occasionally the dose backscattered from a variety of materials for a number of incident energies (24). By 1960 the experimental work of many people had produced further information of the effects on the backscattered radiation of the area of scattering material that was exposed and of the effects of the scatterer thickness for various materials and angles of incidence (3, 4, 5, 14, 25, 26).

In many shielding problems a knowledge of the total back-scattered energy or dose was sufficient to predict the dose received in a given situation. For the dose transmitted by ducts with right angle bends it was observed that the values calculated under the assumption that back-scattered radiation was emitted isotropically were in reasonable agreement with the values observed experimentally (27, 28). This agreement usually involved situations in which scattered radiation was emitted normal to a surface. More detailed duct experiments clearly showed the presence of multiply scattered radiation (29). When this was removed through the use of absorbing Pb liners it was evident that the radiation scattered from the directly exposed areas could be highly anisotropic when detected at scattering angles that approached the plane of the scattering surface. Subsequent work showed that the degree of anisotropy depended greatly on the angle of the incident radiation. Monte Carlo calculations were expanded and used to produce many more case histories so that tables of differential backscatter - that is the backscatter per unit solid angle of emission - were obtained in terms of energy, numbers of γ's or dose (24, 30, 31, 32). The differential scatter coefficients are usually described as differential energy, number or dose albedos where the term dose albedo appears to have a different definition for different authors but can usually be manipulated to yield the total dose albedo defined by Chilton as the ratio of the dose due solely to the reflected radiation from a plane uniformly illuminated by a broad parallel beam of γ's to the dose due solely to the direct radiation. At present the available calculations outnumber the available experimental checks. The USNRDL has been running an extensive program in which the differential dose albedos produced by broad beams of Co^{60} and Cs^{137} γ's incident on slabs of concrete have been measured with a collimated detector for various angles of incidence (33). An alternate method of measuring differential dose albedos would be to use a collimated source and isotropic detectors at a fixed distance from the irradiated area. This was the method used in some recent work at DRCL for Cs^{137} γ radiation incident on slabs of concrete, iron and lead and I will again digress in order to describe this work (34).

The angles of incidence studied were 0, 30 and 60° to the normal and the detectors were small ionization chambers arranged on a 1/4 sphere centered on the irradiated area. It was noticed that the scattered dose distributions obtained when concrete was irradiated at 60° were reduced by placing Pb inserts in the concrete slab beyond the region that was directly irradiated. This indicated that a significant amount of the backscattered γ's emerged at some distance from the point at which their incident parent γ rays entered the medium. In order to obtain the differential dose albedo it was necessary to correct for the radial distribution of these points of emission and this was accomplished with a Monte Carlo program run for this purpose. For an angle of incidence of 60° the corrections to the observed dose distributions were only a few percent except at the forward scattering angles close to the plane of the scatterer where they approached 30% for concrete, 10% for iron and 4% for lead. At smaller angles of incidence the corrections were much less and depended mainly on the finite size of the beam rather than any significant spread beyond the beam region.

As shown in the Transactions, the Monte Carlo program was used also to indicate both the range of the point of emergence of a backscattered γ from its point of incidence and the number backscattered from a last scattering position at a depth greater than the indicated limit.

The differential dose albedos obtained in the plane of incidence are listed in Table 2 of the Transactions. These were obtained with slabs of material sufficiently thick that increasing their thickness would have little or no effect on the observed distributions with the exception of the values listed for iron exposed at an incident angle of 0°. Here the slab was only 1/2" thick and in the next slide (Fig. 6) we have shown the effect of varying the slab thickness on the dose distribution in the plane of incidence. Judging from the work of others (26) the thicker slab should be more than sufficient to approximate a semi-infinite medium as far as backscatter is concerned. The concrete slabs used were 4" thick and the Pb slabs 1/2" backed by 1/2" of iron. A test with 7" concrete and normal incidence produced distributions within 3% of those shown in the table.

The differential dose albedos listed were combined with their values for other angles and integrated to yield a total dose albedo which can be pictured as the extent to which the dose received by a detector in front of a wall exposed to a broad beam of Cs^{137} γ radiation is enhanced by scattered radiation from the wall. These values are shown in the following slide (Fig. 7), where a_T is the total dose albedo and α is the angle of incidence of the Cs^{137} γ radiation.

The differential dose albedos observed at all angles can be examined as a function of the angle of deviation between the incident and emergent γ rays. The next slide (Fig. 8) shows the values observed for concrete exposed to Cs^{137} γ's incident at 60° and for comparison the relative differential dose values expected on the basis of 1st scatter are shown as a dashed line. Here ϕ refers to the angle between the incident and emergent rays so that (180-ϕ) is the angle through which the incident ray has been deviated. The angle ψ is the angle from the plane of incidence to an emergent γ measured in the particular plane of emergence that is perpendicular to the plane of incidence. That is - a constant value of ψ indicates a constant deviation from the plane of incidence. Clearly at small angles of ψ - that is close to the plane of incidence - there is indication of a large 1st scatter component to the distribution and only at angles close to the scattering surface does this fall off. The next slide (Fig. 9) shows corresponding results for an incident angle of 30° where the correlation is less and the next slide (Fig. 10) shows the case of normal incidence and here there is very little evidence of 1st scatter. These slides are the last of the digressions into DRCL measurements but their indication of the role of 1st scatter under certain conditions leads into another most useful development in the study of backscattered radiation and that is the summing up of the masses of empirical data both experimental and from Monte Carlo calculations in terms of simple formulae. The recent success of Chilton and Huddleston (35) in presenting Raso's Monte Carlo calculations (32) of differential dose albedo in a semi-empirical formula dependent on the angle of deviation and on the angle of incidence is most gratifying and we will hear more of the use of this formula later this morning.

The third of our general categories - that of the transmission of radiation through a slab was the first to be studied intensively for shielding purposes. Since most of the earlier measurements were directed to the solution of specific problems they had only a limited usefulness in developing a general penetration analysis. However the study of various simplifications to the barrier radiation transport problem such as considering only energy degradation or the results of 1, 2 or 3 scatterings or the limiting ratio of scattered to primary radiation at great depths, gave a qualitative picture of the behaviour of radiation (36, 37). Following the success of the moment method of calculating the flux of scattered radiation as a function of energy and distance to 15 mfp or so from a source in an infinite homogeneous medium (38), much of the work on barrier shielding was devoted to determining methods in which the infinite medium calculations could be applied to barriers with a finite thickness. At this stage, of course, the problem was mainly the overall shielding of homogeneous slabs. During the 1950's the attenuation of water, concrete, Al, iron and lead was measured by a number of workers using mainly the γ radiation from Co^{60}, Cs^{137} and Au^{198} not only for normally incident radiation but also for radiation incident obliquely onto a barrier (5, 39, 40, 41). During this same period Monte Carlo calculations became popular. With the development of more efficient techniques for extending the number of histories and with the availability of faster computers this rapidly became the most popular method for radiation calculations involving finite geometries. In particular Berger and Doggett at the NBS compared the shielding parameters of slabs with their corresponding values in an ∞ medium, and showed that the differences between the shielding factors calculated using infinite medium results and those obtained for finite shields were small except for low source energies and light materials (42). Using their correction factors good agreement is generally observed between calculated and measured values for the shielding provided by simple homogeneous slabs of large lateral extent.

The problem of the attenuation of radiation in heterogeneous shields however was considerably more complicated than the case of shields of 1 material only and Monte Carlo calculations were applied to a number of shield materials and various energies and angles of incidence. The available calculations considerably outnumber the observations (24 and 43). From the calculations, rules of thumb have been obtained to indicate the extent to which the shielding of a heterogeneous shield may be determined by applying the infinite homogeneous medium factors of only one of the shield components to a slab with the mass thickness of the actual barrier provided that the slab components were not too dissimilar in their infinite medium parameters. However if the shield was composed of alternating layers of high and low atomic number such as lead and water, at low energies the order of the materials was very important and rules of thumb were less reliable. For the particular case of a point source on the surface of a heterogeneous shield Broder has proposed a formula that uses the sum of the differences of homogeneous infinite medium factors calculated for each shield component at a distance in the corresponding infinite medium equal to the mass distance in the actual shield (44). The values obtained from this formula were within 10% of the values observed for a Co^{60} source and shields with wall thicknesses ranging from 0.7 to 15 mfp and consisting of various assemblies of polyethylene, Al, Fe and Pb. For successive thin layers it was noted that agreement was even closer when the correction factors of Berger and Doggett (42) were applied to the infinite medium factors. Subsequent measurements at higher energies of 2.76 Mev and also at an effective energy of 6.4 Mev have shown excellent agreement with the values calculated by this rule for up to 3 layers of polyethylene, Al Fe and Pb in various arrangements ranging up to 8 mfp in thickness (45).

So far only the overall shielding of a slab has been discussed. As in the case of backscatter from a surface there are situations in which we require the detailed angular dependence of the radiation emerging from a slab - ideally for a range of incident energies and angles of incidence and for a range of slab materials and thicknesses.

The first measurements of these distributions appear to be those of Whyte in 1955 for a Co^{60} source at the surface of a concrete barrier of variable thickness where a scintillation spectrometer was used as his detector (46). Since then measurements have been reported for Cs^{137} γ's and concrete (47), for Co^{60} γ's and water (48), 8-10 Mev bremsstrahling on Pb (49), for Co^{60} γ's and Fe (50), and in particular the work at USNRDL (51, 52, 53) where extensive measurements have been made of the angular and energy distributions produced by Co^{60} and Cs^{137} γ's incident on slabs of Al and Fe at various angles of incidence.

The Monte Carlo technique has been used to calculate detailed angular dose distributions of the radiation emitted from slabs of various thicknesses. The recent work by Raso (32) for concrete slabs of 1/2 to 4 mfp thickness exposed to γ energies from 0.2 to 10 Mev has been compared with the work at NRDL. Details of these programs have been reported at a recent ANS meeting (53) and where the distributions are comparable there appeared to be reasonable agreement.

For a heterogeneous barrier, the extent to which successive layers of different materials could affect the distribution of radiation scattered from the final wall to air interface is yet unknown although a program has been written for up to 3 layers (54).

From this short survey of the effects of interfaces on scattering as far as shielding is concerned it might appear that our understanding of what goes on as γ radiation passes and repasses from one medium to another is qualitative only and that the empirical information that we possess merely puts limits on what could be deduced from studies that ignored boundary effects. For much shielding work this is sufficient and we can usually be satisfied to have empirical factors that multiply the results of a simple computation provided we know their reliability and provided they are not too difficult to apply. Consider the situation in each of the categories discussed. For a source at an interface simulating air-ground in density, experiment is in reasonable agreement with the empirical correction factors to be applied to an infinite air medium in all except the close-in positions.

Further experiments will show the detailed effect of different ground materials but the dose at low heights above a smooth uniformly contaminated interface could probably be calculated already to within 15% for any ground material. If the interface is rough the effect on the dose close to the surface is still not well known and a suitable method of relating the effect to the degree of roughness has yet to be devised.

The overall backscattering of radiation from an irradiated surface is reasonably well understood for a variety of materials, energies and angles of incidence - for particular cases agreement of calculations and observation are often within a few %. The development of semi-empirical formulae to describe the detailed angular distributions is of course most useful for shielding calculations.

For radiation transmitted through barriers the detailed exit distributions, for homogeneous walls of limited thicknesses, have been calculated and reasonable agreement appears to be observed in certain angular limits. Experimental checks at all angles would be desirable and if agreement is reasonable some method of summarizing the distributions would be very useful. For the overall shielding provided by a homogeneous barrier there are sufficient data available to encourage the appearance of formulae relating the observed shielding to infinite medium factors. For heterogeneous shields more measurements are required to test proposed formulae for the gross shielding. As for the effects of barrier composition on the exit dose distributions this is still a matter for conjecture. In addition for a barrier, either homogeneous or heterogeneous, little is known about the behaviour of radiation that emerges into a duct in the barrier, yet at high levels of shielding protection these are all effects that must be studied if shielding calculations are to be reliable.

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A SOURCES AT AN INTERFACE.

B RADIATION BACKSCATTERED FROM AN INTERFACE.

C RADIATION TRANSMITTED THROUGH SLABS.

FIG. 1

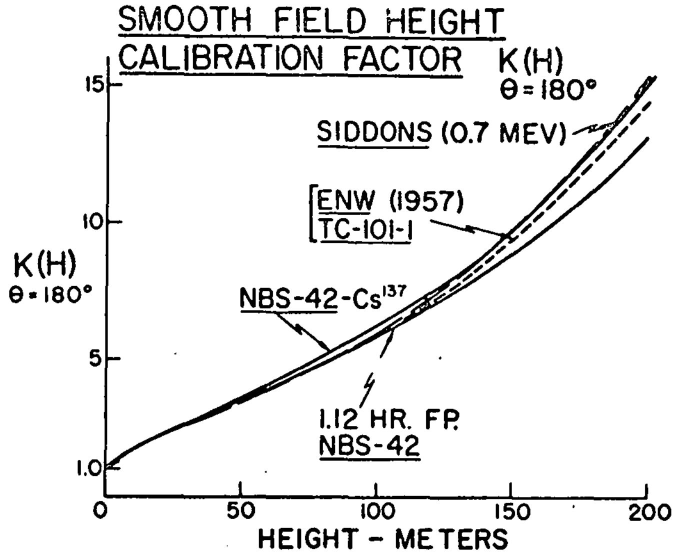

FIG. 2

THEORIES OF DOSE REDUCTION DUE TO GROUND ROUGHNESS

PROPOSAL		ACTUAL DOSE (1 M) / DOSE (1M) SMOOTH PLANE
IGNORE GROUND ROUGHNESS		1.00
EMPIRICAL FACTOR	(E.N.W.)	0.70
	(RAND)	0.87, 0.58
ADD EQUIVALENT HT. (NBS-42)		0.52
CONSIDER FALLOUT BURIED	1"	0.32
	3"	0.14
CONSIDER UNIFORMLY MIXED	1"	0.49
	3"	0.30
SKYSHINE ONLY		0.11

FIG. 3

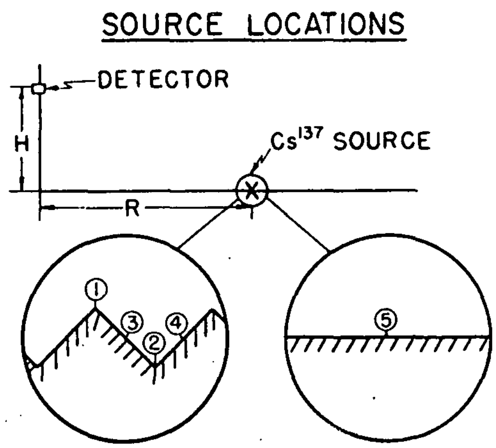

FIG. 4

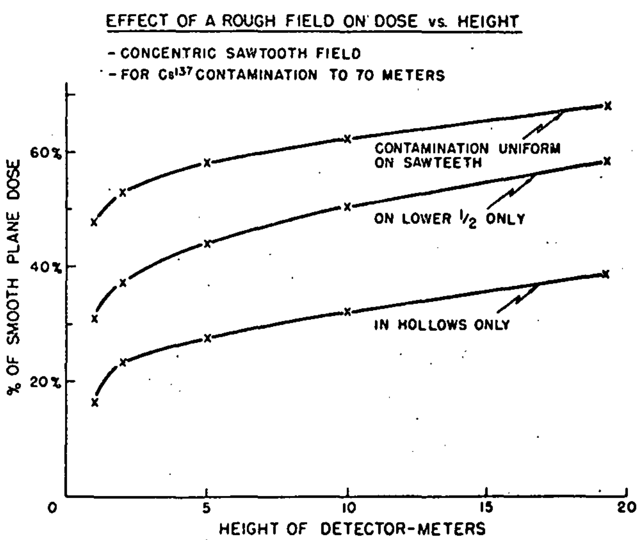

FIG. 5

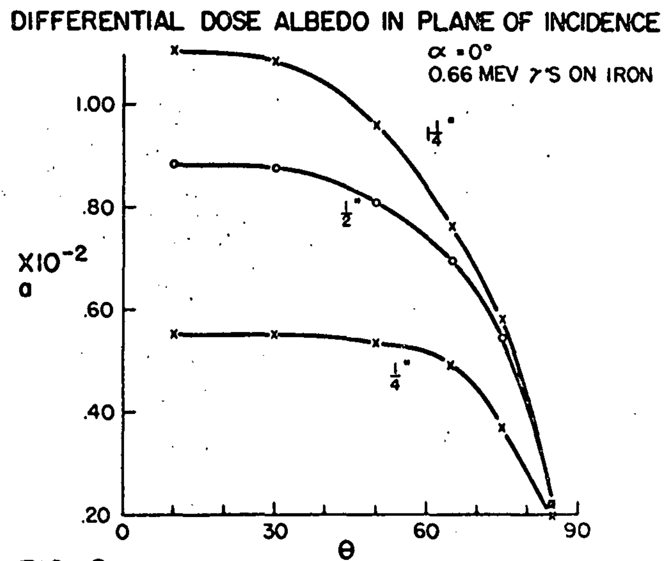

FIG. 6

a_T – FOR 0.66 MEV γ'S

	$\alpha \doteq 0°$	$\alpha = 30°$	$\alpha = 60°$
CONCRETE	.17	.17	.17
IRON	.11	.11	.13
LEAD	.013	.023	.045

FIG. 7

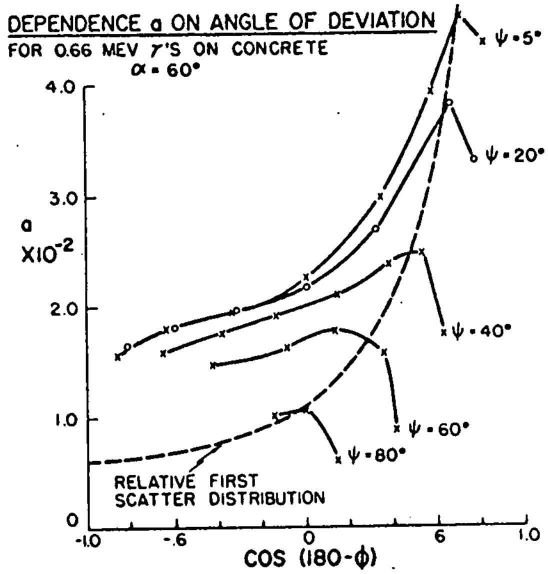

FIG. 8

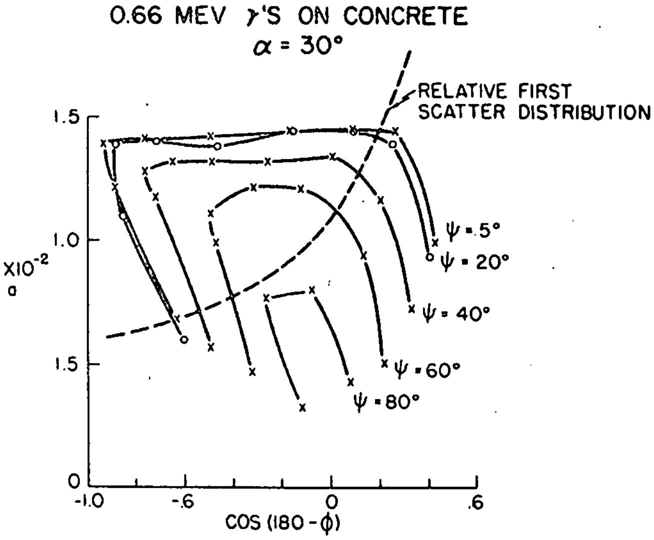

FIG. 9

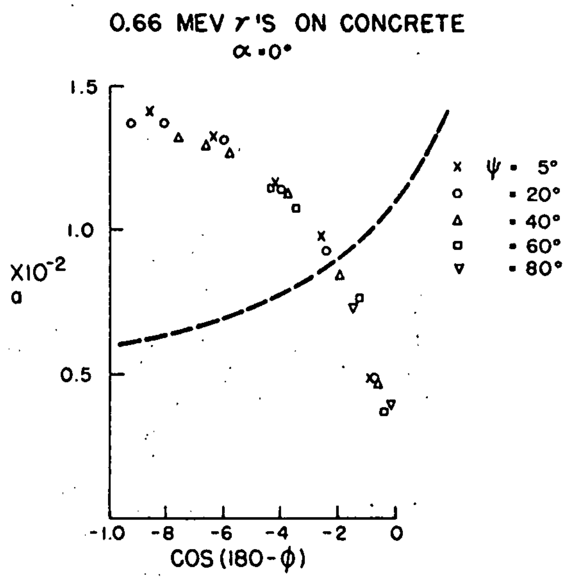

FIG. 10