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TERRAIN EFFECTS ON PROMPT TACTICAL NUCLEAR RADIATION ENVIRONMENTS

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Science Applications, Inc.
2109 W. Clinton Avenue
Huntsville, Alabama 35805

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Effects of terrain on prompt dose to personnel are determined from representative tactical nuclear weapons. Terrain features considered include forest cover, topography, and small bodies of water. Calculations with both idealized and real topography were performed for a region in Central Germany. A parameterization of idealized terrain features was derived.

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1. SUMMARY

This report describes an investigation of the effects of terrain on the prompt total dose to personnel from representative tactical nuclear weapons. Three types of terrain features were considered; a dense forest, topography, and small bodies of water.

In Section 2, the general background and scope of this investigation are discussed as it relates to possible implications on tactical nuclear weapon military systems studies. Previous data and calculations relating to terrain effects are discussed and the development of the three classes of terrain effects problems is described. Both idealized topographical features and real terrain descriptions for a region in Central Germany were investigated.

Section 3 presents the results of the calculations for the effects of a dense forest and the effects of topography.

Section 4 discusses the results of the calculations and suggests a parameterization of the effects of topography that appears to reasonably describe the results obtained in Section 3.

The two major conclusions of this investigation are the following:

1) The protective effects of a dense forest on prompt tissue dose are significantly smaller than estimated previously, and

2) Terrain protection factors where topography shadows the weapon burst from the target can be as high as a factor of 3 - 5 for commonly occurring terrain and a factor of 8 - 10 or more in isolated situations.

2. INTRODUCTION AND BACKGROUND DISCUSSION

2.1 Problem Scope

The consideration of the effects of terrain on prompt nuclear radiation environments from tactical nuclear weapons is a major departure from the usual treatment of the earth's surface as an infinite flat plane. Various natural terrain features can alter the nuclear radiation environment that would exist or would be predicted if the earth's surface were indeed a flat plane. This alteration of the nuclear radiation environments due to natural terrain features will be referenced herein as "terrain effects." The dictionary defines terrain as the physical features of a tract of land. Physical features that are considered include topography, vegetation cover, and surface material (ground or water). This investigation does not, for example, consider curvature of the earth's atmosphere, though a departure from a "flat earth", it would not be considered a physical feature of terrain.

It will be seen that terrain can provide significant protection to locations which are not in line of sight of a nuclear weapon burst. These protection factors are of interest to predictions of both target and non-target damage in a tactical nuclear weapon engagement. Protection factors afforded to non-targets (that is personnel or material which is not the intended target yet which are in the range of the damaging effects of the weapon) would be of interest for reducing collateral damage. On the other hand, the effects of terrain may reduce target damage which may be taken into account in survivability/vulnerability studies. Although it is not the objective or intent of this investigation to assess the impact of terrain effects on the survivability/vulnerability of military systems, such considerations have weighed heavily in defining the scope of this study. Rather, it is the purpose of this investigation to provide data on terrain effects so that such system evaluations can be performed.

As the title of this report indicates, the terrain effects of interest are those pertinent to tactical nuclear weapons. The only implication of tactical nuclear weapons as opposed to strategic or other nuclear weapons is a low to intermediate weapon yield, generally tens of kilotons in yield or less. The distances over which such weapons produce damage levels of military interest are usually less than 2 kilometers. Thus terrain features, and topographical features in particular, over a geographic area of only a few square kilometers would be of interest. Particularly rugged or irregular terrain over which military land operations would be precluded would not be of interest even though large terrain effects might be observed.

This investigation considers only the penetrating prompt nuclear radiation produced by a nuclear weapon. Prompt nuclear radiation includes both neutrons and gamma rays produced in the weapon as well as secondary gamma rays produced from neutron interactions in the atmosphere, ground, or other surface material (vegetation, water). X-rays are not considered because of their limited penetration in the atmosphere. Delayed fission product radiation has not been considered in this investigation, thus the validity of the results may be limited to weapon yields less than 100 kilotons. The effects of terrain on fallout radiation is a different problem altogether and was not considered in this study.

2.2 Previous Information on Terrain Effects

Only two references have been discovered in the literature which could contribute to the present analysis of terrain effects on prompt radiation. One is a report of test data taken in the Nevada desert which, due to unfortunate circumstances, yielded no useful information. The other is an earlier estimate of the effects of forest cover on prompt radiation which will be used for comparison with the present calculations.

Shot Smoky of Operation Plumbob was conducted in Nevada on August 31, 1957. The device was detonated from a 700 foot tower with a yield of approximately 44 kilotons. One of the objectives of Shot Smoky was to observe and take data on the effects of rough and sloping terrain on airblast phenomena and on neutron flux data. Foil activation data was taken along three lines from ground zero, one a relatively flat slope, the second a sharply rising but relatively smooth slope, and the third a rising and very irregular line. These data are the only experimental data that have been found relating to the effects of terrain on nuclear radiation environments.

Unfortunately, the test was not entirely successful due to difficulties in recovering the foil data and to asymmetries in the experimental arrangement. Quoting from the report of the experiment[1]:

> A quantitative evaluation of the effect of terrain on neutron flux based on data obtained from Shot Smoky is impossible due to the design of the device. This device (had) ... a large lead and paraffin slab below. The neutron flux from the device, therefore, was not symmetrical. Although the north line, which was run to the top of a high hill, showed higher flux values than the south line which was run along level terrain, it would be extremely presumptuous to attribute these higher values to a particular terrain feature in question. The east line exhibited a definite variation which could be attributed to the rolling terrain. However, quantitative measurements of this effect was not possible. This data as it applies to the effect of terrain on neutron flux can be considered inconclusive at best.

If warranted, it may be possible to reanalyze these data including the asymmetries of the source, but the current situation is that there exists no useful experimental data related to the effects of terrain on nuclear radiation.

Previous estimates of the attenuation of nuclear radiations due to forests have been made[2]. Table I gives the estimated transmission factors for neutrons and gamma rays through two types of forests and for two burst heights. Though no documentation of the basis for the estimates is available, these transmission factors appear to consider only line of sight attenuation and neglect build up and scattering effects.

Table I. Previous estimates of the transmission of neutrons and gamma rays through forests.*

Particle Type	Transmission Factor	Forest Type	Height of Burst ft.	Height of Burst meters	Slant Range, meters
Neutron	0.1	coniferous	0	0	325
			136	41.45	900
		rain	0	0	125
			136	41.45	275
	0.01	coniferous	0	0	650
			136	41.45	1800
		rain	0	0	250
			136	41.45	525
Gamma Ray	0.1	coniferous	0	0	1300
			136	41.45	3000
		rain	0	0	500
			136	41.45	900

*Tabular data read from figure in U. S. Army Combat Development Command document ACN 4260 (reference 2).

2.3 Objectives of Investigation

The objective of this work is to provide calculational data on the effects of specific terrain features on the prompt personnel dose from representative tactical nuclear weapons. The terrain features that are investigated include:

1) dense forestation
2) topography (hills and valleys)
3) bodies of water (rivers, lakes)

3. METHODOLOGY

In this chapter, the methods and data used in the calculations to be reported will be described. The inclusion of terrain features in the radiation transport calculations resulted in several complications requiring some special modifications of the transport methods usually employed for air/ground calculations for a smooth flat earth. The rationale leading to the formulation of the matrix of calculations that were performed will be described.

3.1 Transport Methods and Results of Previous Air/Ground Calculations

The analysis of terrain effects on prompt nuclear radiation environments can be considered as an extension of the air/ground interface problem. Previous transport analyses of nuclear weapon radiation environments in the vicinity of the air/ground or air/water interface have considered the interface ideally as an infinite plane [3,4,5]. Recent models of weapon environments in the vicinity of the air/ground interface also consider the interface to be an infinite plane [5,6,7]. This treatment of the air/ground interface as a plane can probably be explained by: 1) The original use of air/ground calculations to compare with experiments in which a smooth flat ground was a good model; and 2) method limitations and additional complicity of a non-ideal air/ground interface.

Reference 5* gives the most recent and complete data specific to dose to personnel from tactical nuclear weapons. Therefore, the results of Gritzner et. al. for prompt personnel dose will be taken as the baseline or reference data with which to compare the effects of various terrain features.

Two basic transport methods have been used in the past for air/ground transport calculations, the Monte Carlo method, and the method of discrete ordinates. In general, Monte Carlo methods are used when a three dimensional geometry capability is required, when time dependence is required, or when dose or spectra are required at a limited number of locations. The

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*Reference 5 is a Draft Final Report to DNA under Contract DNA001-74-C-0216. The report is to be published as a Final Report with a DNA report number. The DNA report number is not available at this writing.

discrete ordinates method has been implemented only for one and two dimensional geometries and is most useful when spectral information is required at many locations. The choice of transport method is dictated by that which is most efficient for a particular problem. The prompt personnel dose calculations by Gritzner were adjoint discrete ordinates calculations using the DOTSAI two-dimensional discrete ordinates transport code[8].

The present investigation uses both discrete ordinates and Monte Carlo methods. The reasons for selecting a particular method and mode of calculation will be described in the discussion of the problem development for each of the generic classes of terrain features.

In this investigation both the DOTSAI discrete ordinates transport code and the MORSE Monte Carlo radiation transport code[9] are used. The two codes utilize the same cross section data which facilitates a comparison of results between the two methods.

3.2 Cross Sections, Response Functions and Source Spectra

3.2.1 Cross Sections

The nuclear cross section data used in this work were taken from the DNA working library which is distributed by the Radiation Shielding Information Center as DLC-31[10]. The microscopic cross sections were collapsed to a 23-19 neutron-gamma ray library with the ANISN code [11] weighting with the neutron and gamma ray spectra in air due to a thermonuclear source. The energy group structure for the collapsed cross section library is given in Table II. This group structure was also used for the tactical nuclear weapons radiation environment data base [5].

The air and ground compositions used in this investigation and given in Table III are identical to the compositions used in the tactical nuclear weapons radiation environmental data base[5]. This choice of data was made to facilitate a comparison of the terrain calculations with the flat earth calculations of the previous study.

3.2.2 Response Functions

In order to calculate the dose to personnel from tactical nuclear weapons, a freefield tissue kerma was taken as the appropriate response

Table II. Energy group structure of tactical nuclear weapons radiation environment data base.

Neutron Group	Energy (MeV)	Gamma Ray Group	Energy (MeV)
1	1.5 (+7) - 1.22 (+7)	1	1.0 (+7) - 8.0 (+6)
2	1.22 - 1.00 (+7)	2	8.0 (+6) - 6.0
3	1.00 - 8.18 (+6)	3	6.0 - 5.0
4	8.18 (+6) - 6.37	4	5.0 - 4.0
5	6.37 - 4.96	5	4.0 - 3.0
6	4.96 - 4.06	6	3.0 - 2.5
7	4.06 - 3.01	7	2.5 - 2.0
8	3.01 - 2.38	8	2.0 - 1.5
9	2.38 - 2.30	9	1.5 - 1.0
10	2.30 - 1.83	10	1.0 - 7.0 (+5)
11	1.83 - 1.11	11	7.0 (+5) - 4.0
12	1.11 - 5.50 (+5)	12	4.0 - 3.0
13	5.50 (+5) - 1.11 (+5)	13	3.0 - 1.5
14	1.11 (+5) - 2.18 (+4)	14	1.5 - 1.0
15	2.18 (+4) - 3.35 (+3)	15	1.0 - 7.0 (+4)
16	3.35 (+3) - 5.83 (+2)	16	7.0 (+4) - 4.5
17	5.83 (+2) - 1.01 (+2)	17	4.5 - 3.0
18	1.01 (+2) - 2.90 (+1)	18	3.0 - 2.0
19	2.90 (+1) - 1.07 (+1)	19	2.0 (+4) - 1.0 (+4)
20	1.07 (+1) - 3.06 (+0)		
21	3.06 (+0) - 1.12 (+0)		
22	1.12 (+0) - 4.14 (-1)		
23	4.14 (-1) - 1.00 (-1)		

Table III. Air and ground composition for terrain effects calculations.

Element	Atoms/(barn · centimeter)	
	Air (1.11×10^{-3} gm/cm^3)	Ground (1.6 gm/cm^3)
H		1.753 (-3)
C		1.639 (-3)
N	3.635 (-5)	
O	9.620 (-6)	3.035 (-2)
Na		1.586 (-4)
Mg		2.577 (-4)
Al		6.969 (-3)
Si		1.093 (-2)
K		4.922 (-4)
Ca		1.529 (-3)
Fe		2.795 (-4)

function. In addition, a simplified armor shielded tissue response function was used in order to calculate the dose to personnel within a light armored tank from tactical nuclear weapons. These response functions are tabulated in Table IV. The armor shielded response is based on a spherical model of a light tank. The model had an inside radius of 1 meter and an armor thickness of 6.35 cm. The armor composition is given in Table V.

3.2.3 Source Spectra

In various sections of the calculations, three weapon spectra have been considered which are representative of tactical nuclear weapons. The source spectrum labeled as "Weapon A" is that of a nominal low to intermediate yield thermonuclear weapon. The source spectrum labeled "Weapon B" is similar to Weapon A but with a harder (higher energy) neutron spectrum. The source spectrum labeled "Weapon C" is a slightly degraded weapon fission spectrum.

3.3 Problem Development

This subsection describes the rationale that went into developing the specific problems that were calculated from the defined objectives and scope of this investigation as described in Section 2. The problem development is subdivided into three parts discussing respectively: 1) The effects of dense forestation; 2) The effects of topography; and 3) The effects of bodies of water.

3.3.1 The Effects of Dense Forestation

In order to investigate the effects of dense forestation, it is necessary to develop a quantitative model. Various sources in the literature were searched to develop such a calculational model of a dense forest. Figure 1 illustrates several terms describing forest canopies that will be useful in this discussion. There does not seem to be a standard by which to define the density of a forest; therefore, for this investigation, a measure of the density of a forest canopy is taken to be the weight fraction of vegetation between the shrub stratum height and the primary canopy height. Thus, any brush or vegetation on or near the ground would not be considered and isolated "giants of the forest" which emerge above the primary canopy are ignored.

In the densest of forests (tropical rain forests), the weight fraction of vegetation within the primary canopy is still quite small, probably not

Table IV. Free field and armor shielded detector tissue response functions.

Group [Neutrons]	Upper Energy (eV)	Tissue Kerma Factor (rads · cm²/incident particle) Free Field	Armor Shielded Neutron	Gamma Ray	Total
1	1.50 (+7)	6.36 (- 9)	4.30 (- 9)	3.67 (-10)	4.67 (- 9)
2	1.22 (+7)	5.74 (- 9)	3.77 (- 9)	3.96 (-10)	4.17 (- 9)
3	1.00 (+7)	5.17 (- 9)	3.51 (- 9)	4.03 (-10)	3.91 (- 9)
4	8.18 (+6)	4.87 (- 9)	3.20 (- 9)	3.49 (-10)	3.55 (- 9)
5	6.37 (+6)	4.51 (- 9)	3.02 (- 9)	2.76 (-10)	3.30 (- 9)
6	4.96 (+6)	4.21 (- 9)	2.74 (- 9)	2.06 (-10)	2.94 (- 9)
7	4.06 (+6)	3.98 (- 9)	2.64 (- 9)	1.27 (-10)	2.77 (- 9)
8	3.01 (+6)	3.39 (- 9)	2.47 (- 9)	5.74 (-11)	2.53 (- 9)
9	2.38 (+6)	3.07 (- 9)	2.31 (- 9)	4.24 (-11)	2.35 (- 9)
10	2.30 (+6)	3.05 (- 9)	2.31 (- 9)	4.07 (-11)	2.35 (- 9)
11	1.83 (+6)	2.63 (- 9)	2.08 (- 9)	2.71 (-11)	2.11 (- 9)
12	1.11 (+6)	2.05 (- 9)	1.84 (- 9)	1.08 (-11)	1.85 (- 9)
13	5.50 (+5)	1.27 (- 9)	1.21 (- 9)	7.87 (-12)	1.22 (- 9)
14	1.11 (+5)	4.00 (-10)	3.25 (-10)	2.75 (-11)	3.53 (-10)
15	2.18 (+4)	4.00 (-10)	3.25 (-10)	2.75 (-11)	3.53 (-10)
16	3.35 (+3)	1.96 (-11)	8.91 (-12)	8.19 (-11)	9.08 (-11)
17	5.83 (+2)	3.67 (-12)	1.40 (-12)	4.25 (-11)	4.39 (-11)
18	1.01 (+2)	1.17 (-12)	6.27 (-13)	5.57 (-11)	5.64 (-11)
19	2.90 (+1)	1.11 (-12)	8.12 (-13)	1.04 (-10)	1.04 (-10)
20	1.07 (+1)	1.62 (-12)	8.27 (-13)	1.37 (-10)	1.38 (-10)
21	3.06 (+0)	2.65 (-12)	7.68 (-13)	1.95 (-10)	1.96 (-10)
22	1.12 (+0)	4.26 (-12)	5.67 (-13)	3.07 (-10)	3.08 (-10)
23	4.14 (-1)	9.35 (-12)	1.13 (-13)	6.47 (-10)	6.47 (-10)
[Gamma Rays]					
24	1.00 (+7)	2.42 (- 9)	0.0	7.12 (-10)	7.12 (-10)
25	8.00 (+6)	1.95 (- 9)	0.0	6.03 (-10)	6.03 (-10)
26	6.00 (+6)	1.84 (- 9)	0.0	5.77 (-10)	5.77 (-10)
27	5.00 (+6)	1.59 (- 9)	0.0	4.74 (-10)	4.74 (-10)
28	4.00 (+6)	1.27 (- 9)	0.0	3.67 (-10)	3.67 (-10
29	3.00 (+6)	1.03 (- 9)	0.0	2.86 (-10)	2.86 (-10)
30	2.50 (+6)	8.75 (-10)	0.0	2.16 (-10)	2.16 (-10)
31	2.00 (+6)	7.05 (-10)	0.0	1.49 (-10)	1.49 (-10)
32	1.50 (+6)	5.70 (-10)	0.0	9.35 (-11)	9.35 (-11)
33	1.00 (+6)	4.13 (-10)	0.0	4.18 (-11)	4.18 (-11)
34	7.00 (+5)	2.94 (-10)	0.0	1.91 (-11)	1.91 (-11)
35	4.50 (+5)	2.03 (-10)	0.0	7.01 (-12)	7.01 (-12)
36	3.00 (+5)	1.03 (-10)	0.0	7.04 (-13)	7.04 (-13)
37	1.50 (+5)	6.60 (-11)	0.0	1.22 (-14)	1.22 (-14)
38	1.00 (+5)	3.90 (-11)	0.0	0.0	0.0
39	7.00 (+4)	4.79 (-11)	0.0	0.0	0.0
40	4.50 (+4)	8.37 (-11)	0.0	0.0	0.0
41	3.00 (+4)	8.37 (-11)	0.0	0.0	0.0
42	2.00 (+4)	8.37 (-11)	0.0	0.0	0.0

Table V. Light tank armor composition.

Element	Weight Percent	Atomic Concentration atoms/barn · cm)
Fe	95.63	8.097×10^{-2}
C	0.27	1.063×10^{-3}
Mn	1.03	8.866×10^{-4}
Si	0.48	8.081×10^{-4}
Cr	1.07	9.729×10^{-4}
Ni	0.97	7.813×10^{-4}
Mo	0.55	2.711×10^{-4}

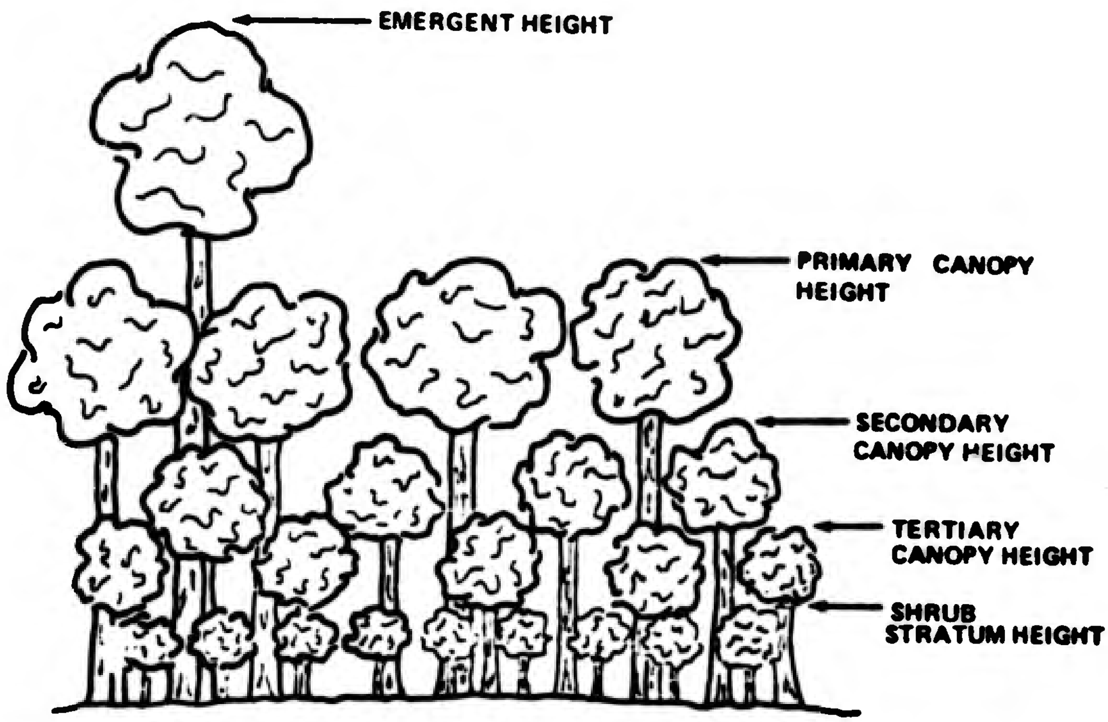


Figure 1. Definitions of terms related to forest canopies.

exceeding 0.0025. However, a forest of such a density would severely hamper if not preclude military land operations. A forest with a 0.0012 weight fraction of wood within the primary canopy height is about as dense as a coniferous forest will grow in a natural state and is chosen as the density of the forest to be considered in these calculations. Within the forest layer the average density is approximately twice that of air.

There is only a small variation in the chemical analysis of wood between various species of trees as can be observed in Table VI. Somewhat arbitrarily, the composition of pine was assumed to be characteristic of the forest layer.

A homogeneous representation of the primary forest canopy was assumed for the calculations. This was felt to be appropriate for very dense forests, though for sparse forests a homogeneous representation would be an obvious error. For bursts occurring directly above the target, there would also be more suspicion about the validity of a homogeneous model. However, for an overhead burst the protection afforded by a forest to dose received by personnel is minimal. Fortunately where a homogeneous representation may be suspect, the effects of a forest layer are expected to be inconsequential. Even if line of sight would exist through a "crack in the forest," the nature of the transport process supports the validity of a homogeneous model for a burst at a slant range.

The physical data for the forest model described in the development above are summarized in Table VII. The unspecified material in wood (primarily ash) was taken to be potassium.

The most efficient method for calculating the prompt personnel dose in a dense homogeneous forest layer was determined to be an adjoint discrete ordinate calculation. By comparing the source energy weighted importance (personnel dose) with similar calculations without the presence of the forest layer, the effects of the forest layer can be determined as a function of source height and ground range from the detector.

3.3.2 The Effects of Topography

Calculations of the effects of topographic features were limited in practice to Monte Carlo methods. Even where cylindrical symmetry could be assumed, numerical limitations and mesh size limitations precluded the use of

Table VI. Chemical analysis of woods[a] (all values in percent).

Constituent	Larch	Pine	Spruce	Oak	Beech
Carbon	49.6	50.2	50.0	49.2	48.9
Hydrogen	5.8	6.1	6.0	5.8	5.9
Nitrogen	0.2	0.2	0.2	0.4	0.2
Oxygen	44.2	43.4	43.5	44.2	44.5
Other	0.2	0.2	0.3	0.4	0.5

[a]Sapwood

Table VII. Forest model physical data.

Primary Canopy Height	-	10 meters
Weight Fraction of Wood	-	0.0012
Wood Density	-	0.7 gm/cm^3
Air Density	-	1.11×10^{-3} gm/cm^3
Wood Composition	-	50.2 wt% carbon 6.1 wt% hydrogen 0.2 wt% nitrogen 43.4 wt% oxygen 0.2 wt% potassium
Air Composition	-	21.0 wt% oxygen 79.0 wt% nitrogen
Mass thickness of forest layer		1.95×10^{-3} gm/cm^3

existing discrete ordinates transport codes. The limitations of discrete ordinates methods are most obvious where line of sight does not exist between the source and detector. Several factors combine to require unrealistic computer resources. These factors include the geometric size of the calculations and the importance of adequate mesh spacing in the ground in the vicinity of both the source and detector.

The study of the effects of topography was approached in two phases. In the first phase idealized topographic features were investigated. The reason for considering idealized topography was to facilitate the development of a model of terrain effects which can be applied to real terrain. In the second phase, calculations were performed with topographical models of actual geographic locations.

3.3.2.1 Idealized Terrain

The selection of idealized terrain features was guided by those considerations discussed in section 1 and by a study of the topography of the Lauterbach region of Western Germany. Two basic types of topographic features were considered, hills and valleys. In a valley the weapon burst occurs between two bodies of land and the line of sight between the weapon burst and target is unobstructed. This geometric configuration was of interest because of the possible enhancement of prompt personnel dose due to reflection of nuclear radiation from the walls or sides of the valley. With a hill the possibility exists for the line of sight between the weapon burst and the target to be obstructed by the hill. The hill would be expected to provide a level of protection to those locations shadowed from the weapon burst.

Figure 2 shows a map of the terrain around Schlitz in the Lauterbach region of Western Germany. The distance between map lines is 1000 meters so that Figure 2 shows an area of about 130 square kilometers. As a reference point, the center of the area shown is approximately $9^{o}34'$ E by $50^{o}41'$ N. The topography of the area can be determined by observing the contour lines. The distance between solid contour lines is 10 meters in elevation and the distance between solid and broken contour lines is 5 meters in elevation. For the area shown in Figure 2, the maximum slope which extends for at least 500 meters appears to be on the order of 15^{o}. Maximum differences in elevation over distances of 2 kilometers are about 150 meters.

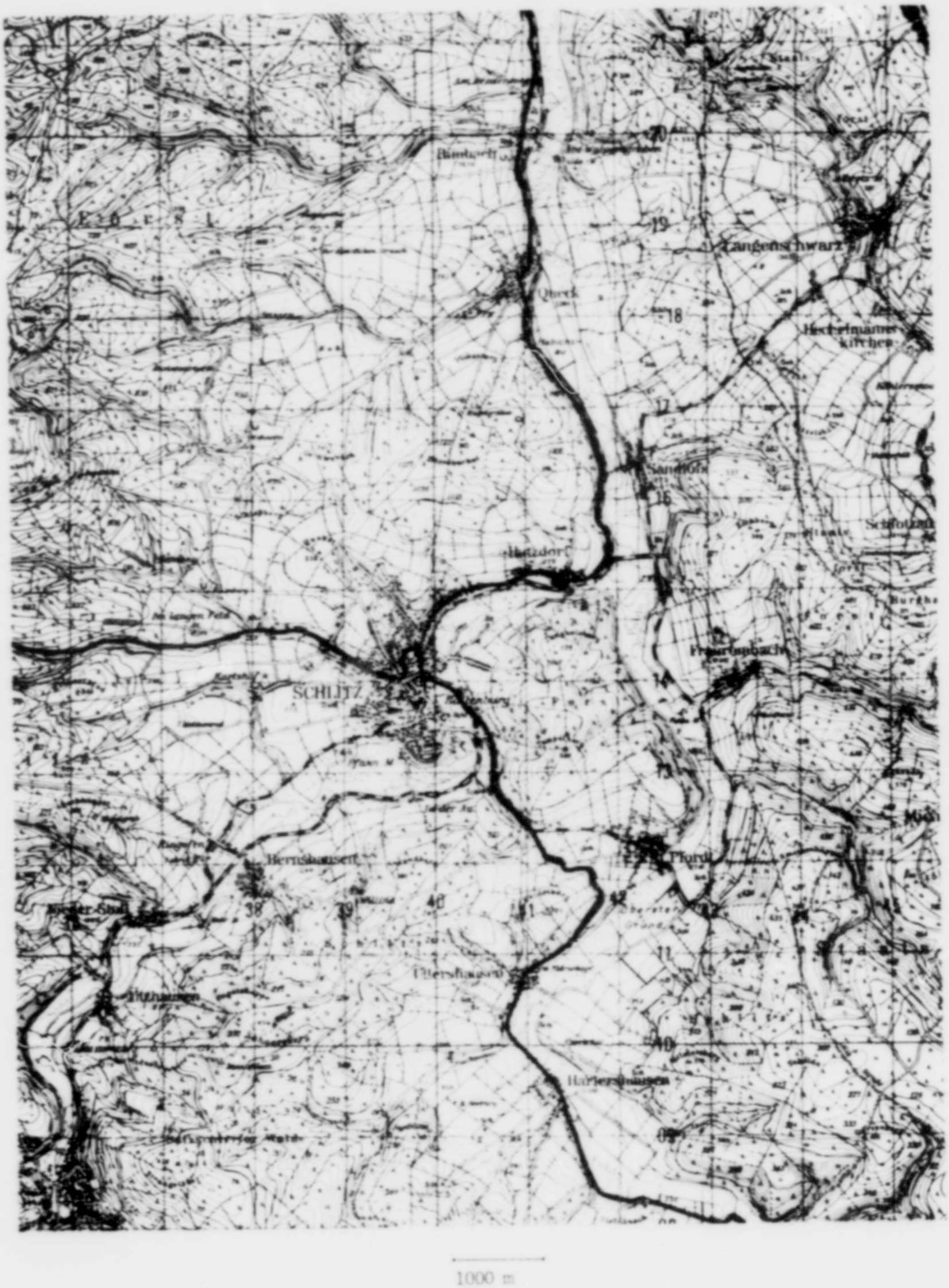


Figure 2. Topographical map of the terrain around Schlitz in Western Germany.

For the idealized topography, cylindrical symmetry was assumed with the burst occurring on the z-axis. Thus, valleys become craters and hills become cylindrically symmetric hills. The motivation for considering cylindrical symmetry was to maximize the efficiency of the Monte Carlo calculations. (The discussion in the results section and analysis section of this report will demonstrate that this simplifying assumption does not bias the final conclusions.)

A series of 15 idealized hill and valley problems were calculated. This minimal matrix of calculations was designed to scope the major effects of terrain on prompt dose to personnel from tactical nuclear weapons. This matrix of idealized terrain calculations that were performed is described in Table VIII. The explanation of the parameters used to describe the idealized hills are given in Figure 3.

3.3.2.2 Real Terrain

Three additional calculations were performed utilizing digitized topographical data for three areas contained in Figure 2. Each of these problems considered an area of approximately 4 square kilometers centered about UTM (Universal Transverse Mercator) coordinates (40, 17), (41, 15), and (41, 12.4) respectively. These coordinates can be located on the map in Figure 2 from the bold numbers printed on the map lines across and up the map. Coordinate (41, 15) can be seen to be approximately 500 meters west of the village of Hutzdorf in the center of the map.

These three problems with real terrain are intended to be used as benchmark problems for comparison with idealized terrain calculations with the intention of developing models of terrain effects. The three areas were chosen because of the particular terrain surrounding the ground zero of the burst points. To facilitate a visualization of the terrain, isometric projections of the regions were prepared for the three regions and are shown in Figures 4 through 11. Figures 4, 5 and 6 show northwest, northeast and southeast projections of the region surrounding coordinate (40, 17). Figures 7, 8 and 9 show northwest, northeast and southeast projections of the region surrounding coordinate (41, 15). Figures 10 and 11 show northwest and southeast projections of the region surrounding coordinate (41, 12.4).

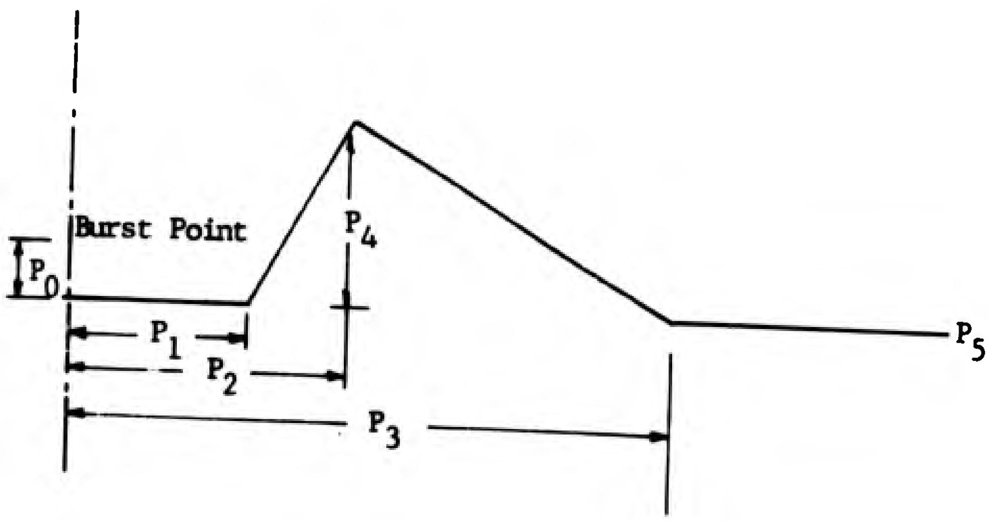
Table VIII. Description of idealized terrain calculations.

Valley Calculations

Problem No.	Weapon Type	Height of Burst Meters	Slope of Valley Walls	Results in Figures
V1	A	40.	15^o	18, 19
V2	A	40.	30^o	20, 21
V3	A	130.	45^o	22, 23
V4	B	130.	45^o	24. 25

Hill Calculations

Problem No.	Weapon Type	Height of Burst Meters	P_1	P_2 (Meters)	P_3	P_4	P_5	Results in Figures
H1	A	40.	100.	200.	300.	100.	0.	26, 27
H2	A	40.	100.	200.	300.	50.	0.	28, 29
H3	A	40.	100.	200.	300.	25.	0.	30, 31
H4	A	40.	100.	200.	300.	100.	100.	32, 33
H5	A	40.	100.	150.	200.	200.	200.	34, 35
H6	A	40.	100.	150.	100.	100.	100.	36, 37
H7	A	40.	200.	250.	300.	-100.	-100.	38, 39
H8	B	40.	200.	250.	300.	-100.	-100.	40, 41
H9	B	40.	100.	150.	200.	200.	200.	42, 43
H10	B	40.	100.	200.	300.	100.	0.	44. 45
H11	A	40.	100.	500.	550.	100.	0.	46, 47



P_0 height of burst

P_1 distance to base of hill

P_2 distance to peak of hill

P_3 distance to rear base of hill

P_4 hill height

P_5 ground elevation behind hill

Figure 3. Parameterization of cylindrically symmetric hills.

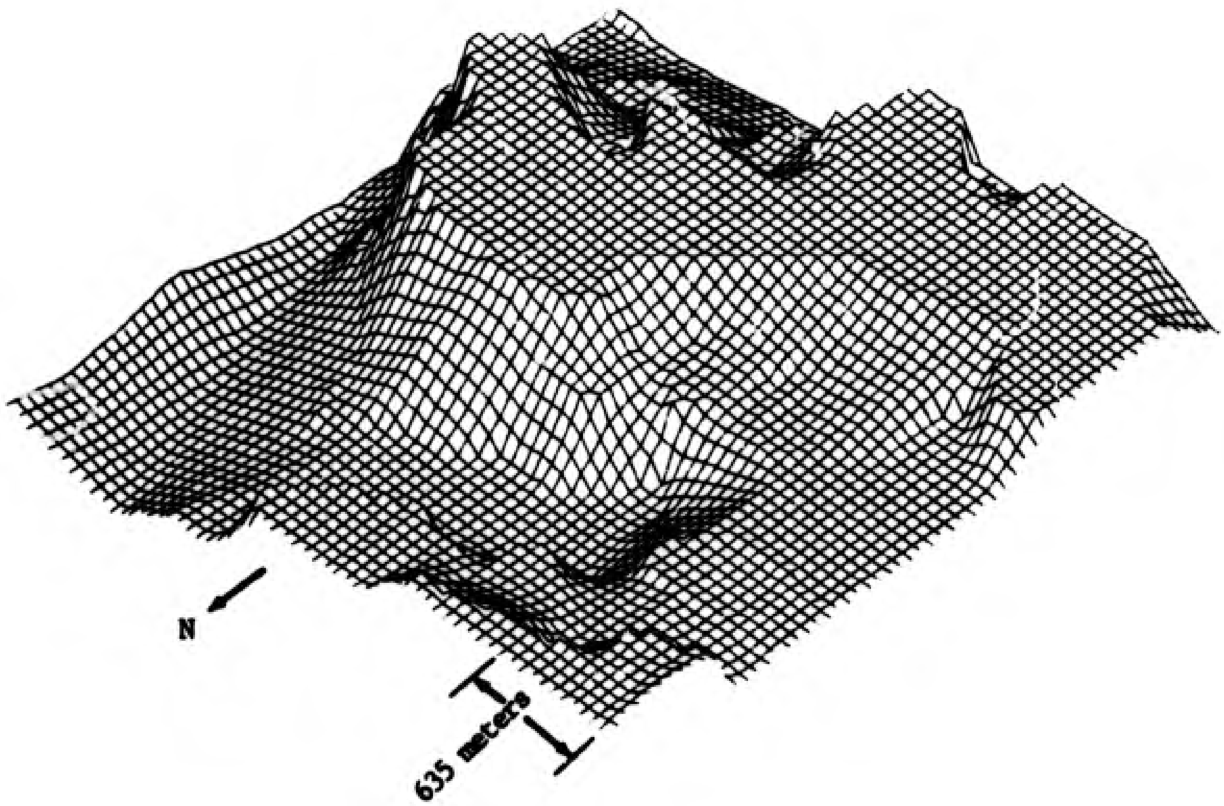


Figure 4. Northwest projection of terrain surrounding coordinate point (40, 17).

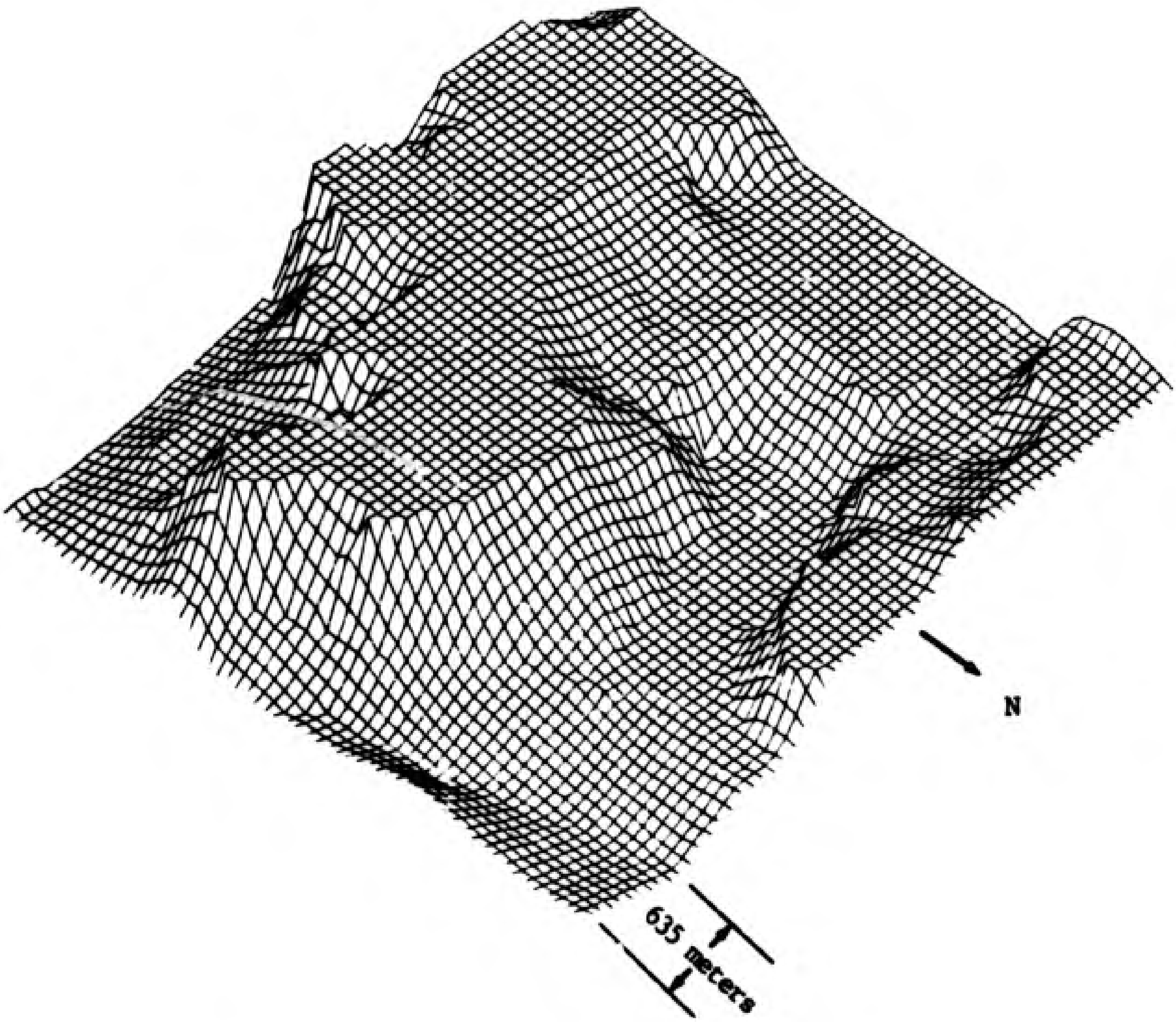


Figure 5. Northeast projection of terrain surrounding coordinate point (40, 17).

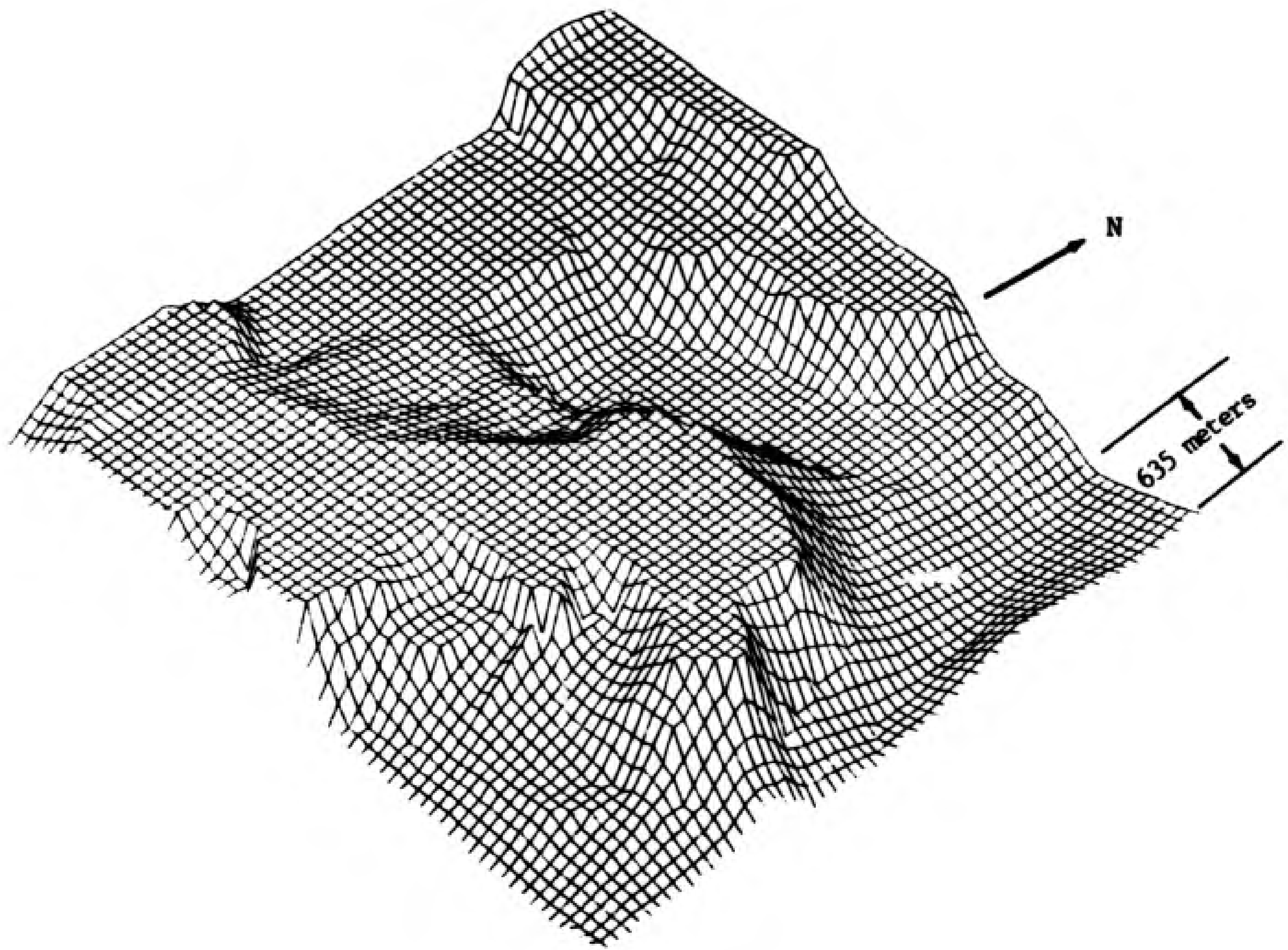


Figure 6. Southeast projection of terrain surrounding coordinate point (40, 17).

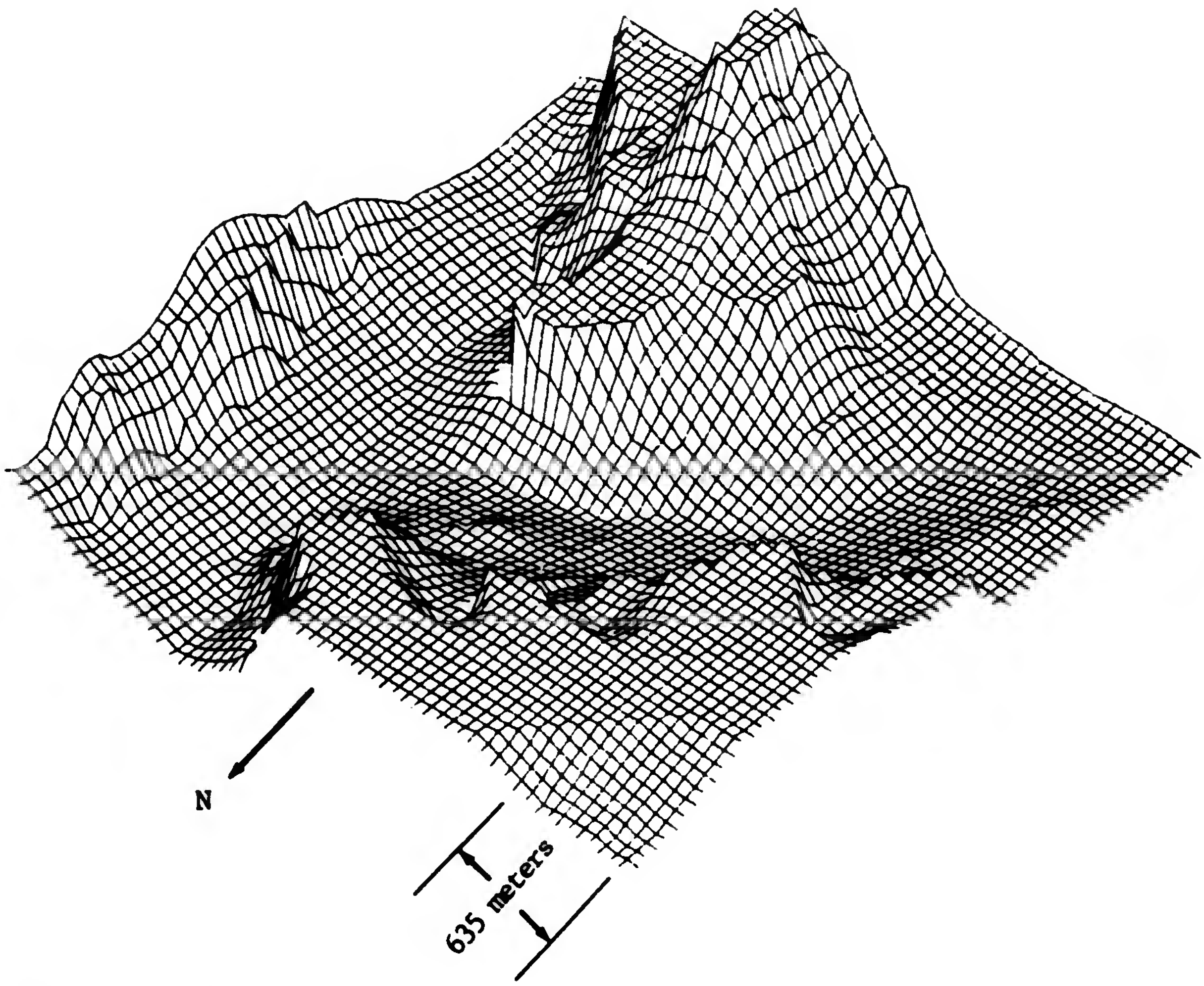


Figure 7. Northwest projection of terrain surrounding coordinate point (41, 15).

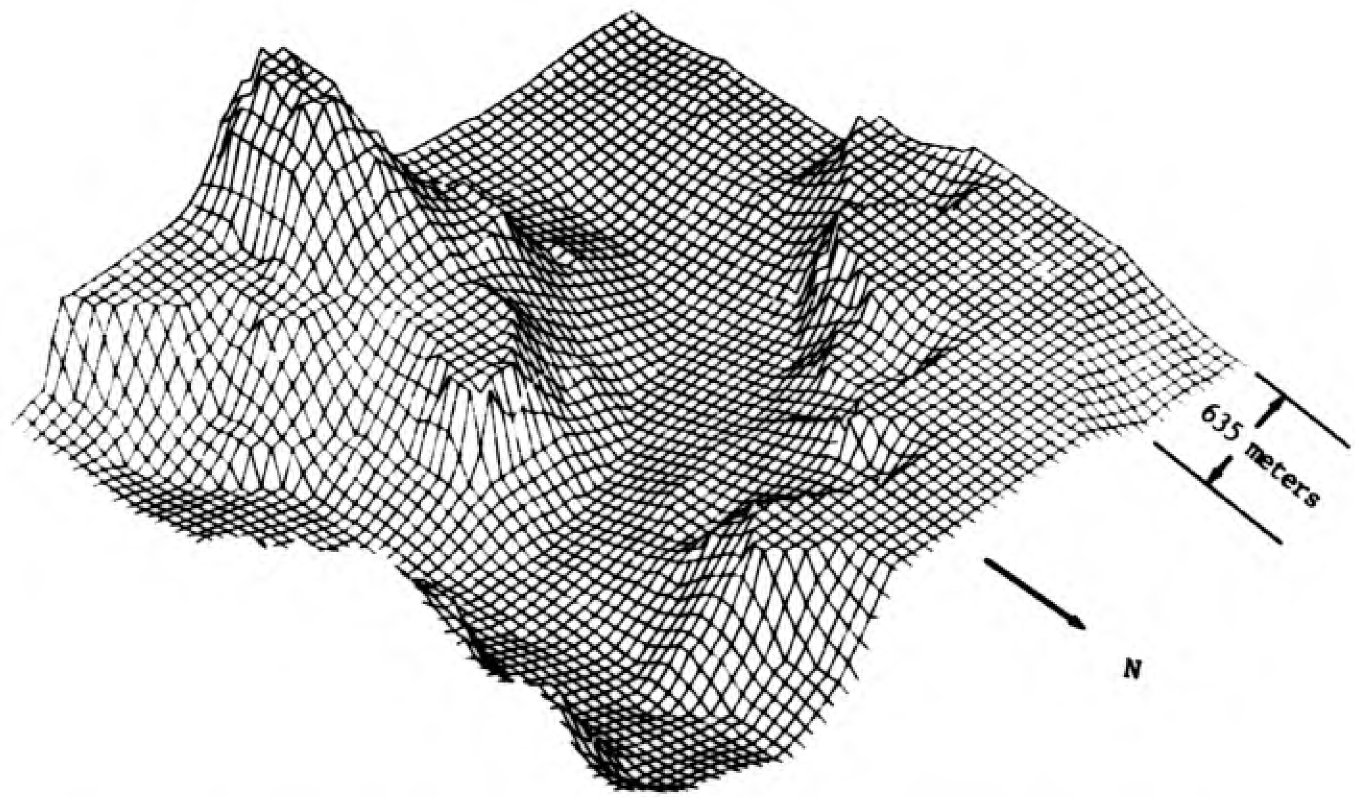


Figure 8. Northeast projection of terrain surrounding coordinate point (41, 15).

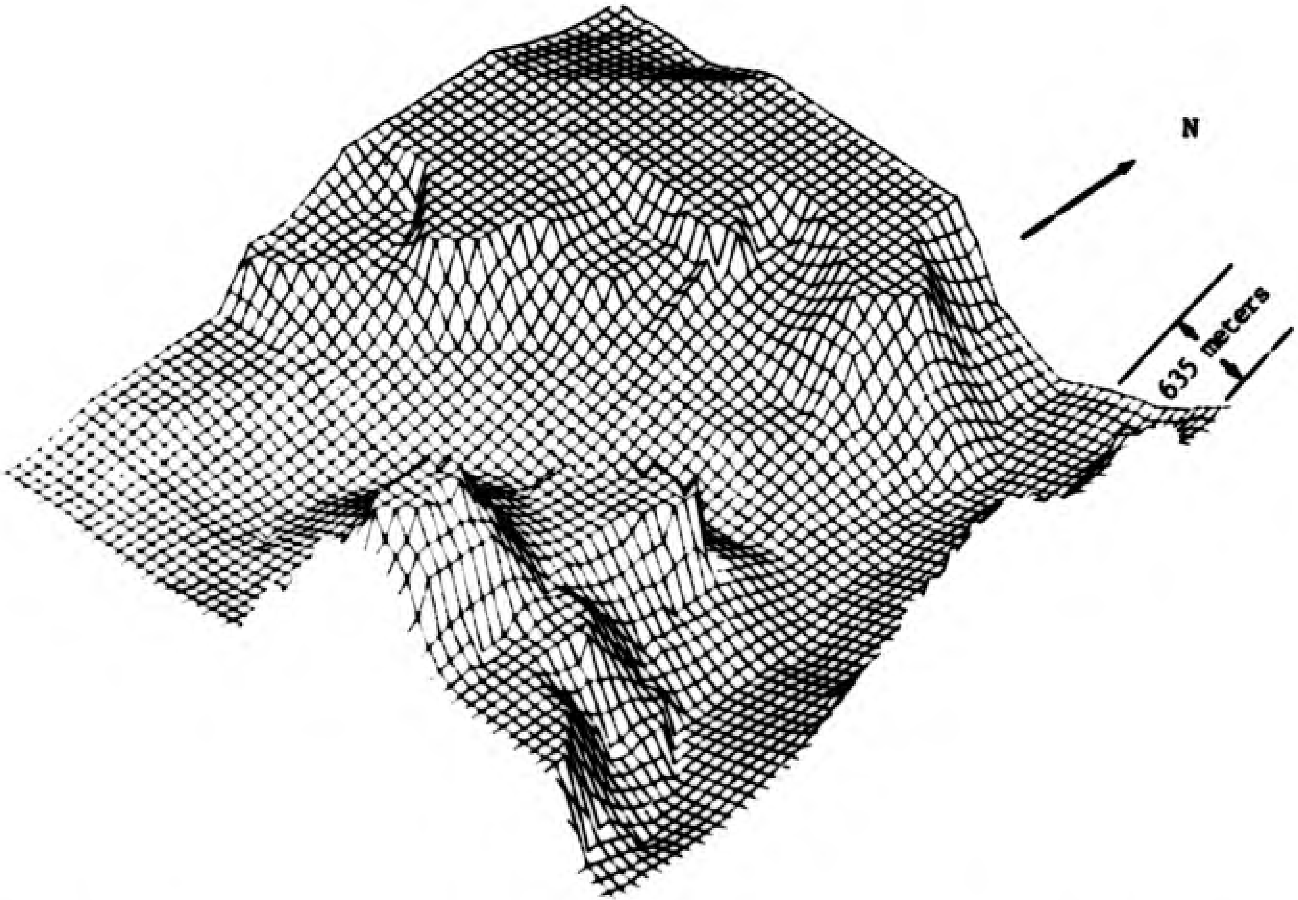


Figure 9. Southeast projection of terrain surrounding coordinate point (41, 15).

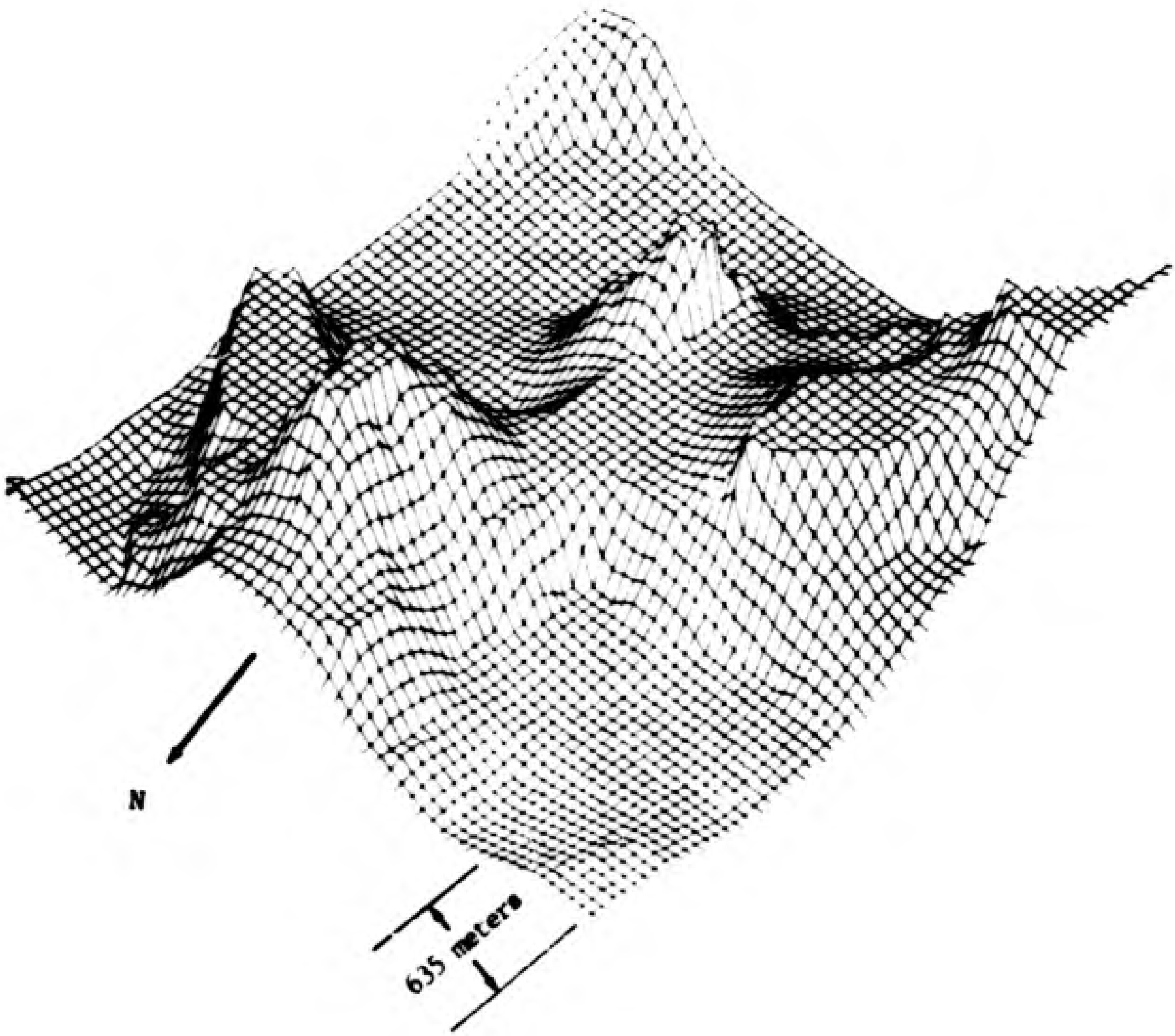


Figure 10. Northwest projection of terrain surrounding coordinate point (41, 12.4)

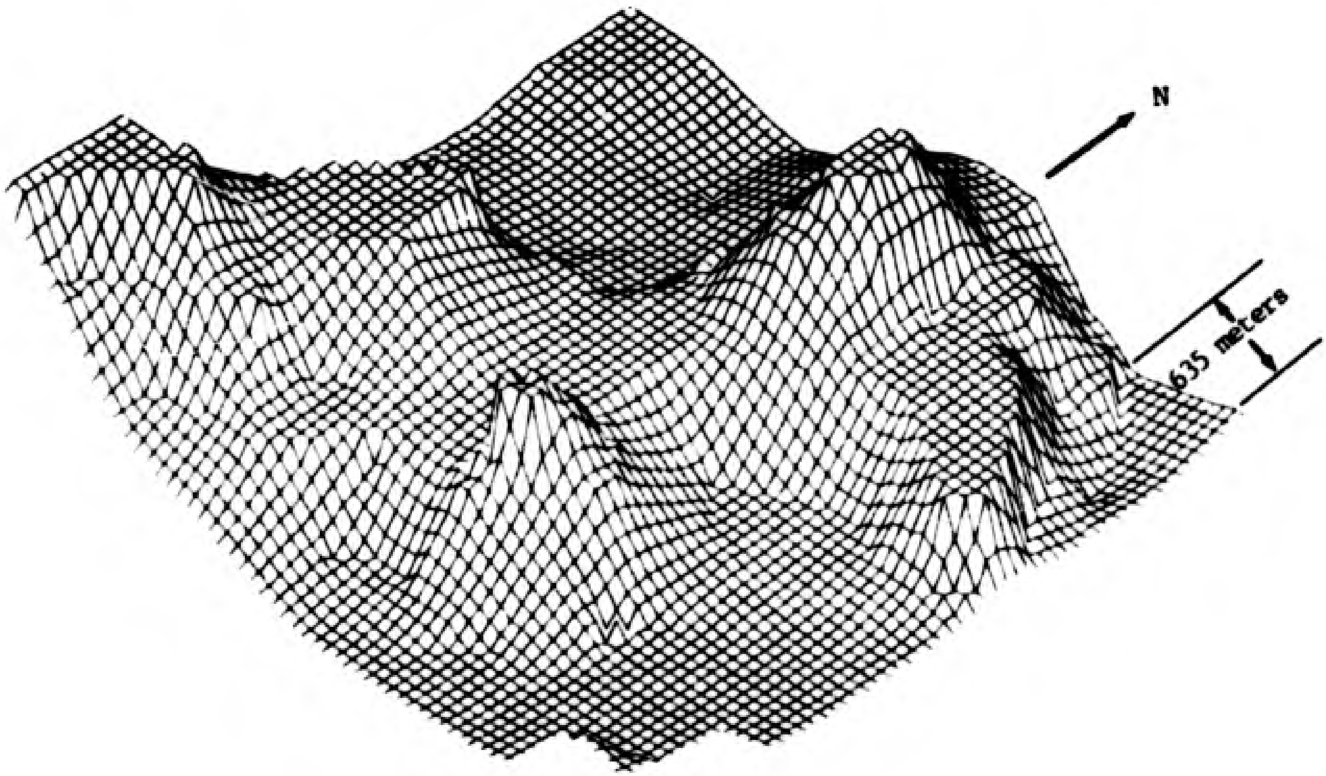


Figure 11. Southeast projection of terrain surrounding coordinate point (41, 12.4).

The distance between grid lines on the projections is approximately 63.5 meters. The vertical scale is expanded to facilitate visualization of terrain features. A northwest projection indicates that the observer is viewing the region from the northwest.

It should be noted that the selection of these three points was somewhat arbitrary and that specific village names in Western Germany are mentioned only to facilitate location of topographical features.

Coordinate point (40, 17) was selected because of the downward sloping terrain from the center of the region to the northeast and because of the hill between the center and southeast corner of the region.

Coordinate point (41, 15) was selected because of its location in the valley near the intersection of the Fulda and Schlitz rivers.

Coordinate point (41, 12.4) was selected because of the saddle shaped terrain with downward slopes to the northwest and northeast and upward slopes to the southeast and southwest.

3.3.3 The Effects of Bodies of Water

The starting point for investigating the effects of bodies of water (rivers and lakes) on the prompt personnel dose from representative nuclear weapons are the previous calculations of nuclear weapon environments in air over water[4, 12]. The results of Pace and Bartine[12] are summarized in Table IX for two weapon spectra. From these calculations, it can be seen that radiation transport in air over water differs significantly from radiation transport in air over ground only for the gamma ray component of the dose from a fission neutron spectrum for small ground ranges. This difference has been attributed primarily to the chlorine content of seawater which would not be present in fresh water bodies.

For tactical nuclear weapon scenarios in military land operations, it is extremely unlikely that the weapon burst and target are both over water. Since the differences between air/ground and air/water are not particularly large in the context of this investigation, it is not felt that small bodies of water such as rivers and lakes would significantly effect prompt personnel dose from representative nuclear weapons. One calculation was performed to

Table IX. Summary of previous air over water calculations.

	Ground Range Meters	Air/Seawater / Air/Ground Neutrons Dose	Air/Seawater / Air/Ground Gamma Ray Dose
Fission Source	100	0.77	2.46
	200	0.7	2.0
	300	0.73	1.81
	400	0.66	1.64
	500	0.68	1.61
	600	0.62	1.53
	700	0.62	1.51
	800	0.63	1.39
	900	0.7	1.36
	1000	0.62	1.33
	1100	0.61	1.29
	1200	0.63	1.14
	1300	0.63	1.28
	1400	0.65	1.2
14 MeV Source	100	0.9	1.0
	200	0.95	1.11
	300	0.89	1.05
	400	0.92	1.04
	500	0.86	1.08
	600	0.80	1.2
	700	0.85	1.09
	800	0.81	1.10
	900	0.74	1.18
	1000	0.75	1.13
	1100	0.78	1.13
	1200	0.73	1.00
	1300	0.76	1.07
	1400	0.73	1.00

demonstrate the insignificant effect due to a river between the source and detector. A burst was assumed to occur over a flat earth with a 40 meter height of burst. A region of water 100 meters in breadth was considered in an annular ring extending between 200 and 300 meters from ground zero. The surface of the water was at ground level and the depth of water was essentially infinite.

3.4 Terrain Model Development for Topographic Calculations

Digitized topographical data on magnetic tape from the Defense Mapping Agency was utilized for the real terrain calculations. These data are obtained by an automated scanning of contour maps to yield digitized elevations on a regular array of map points. A scanning interval of .01 inch on a 1:250000 scale map translates to an interval of 63.5 meters. This resolution of elevation data is felt to be adequate for the present purposes. However, the amount of data points contained in a 4 square kilometer region is quite large, numbering approximately 3600 elevation points.

The combinatorial geometry routines of the MORSE Monte Carlo transport code used in the calculations were not designed to efficiently accommodate such large and irregular geometries. In principle the terrain surface could be described by constructing 3600 arbitrary polyhedral surfaces. However, a more efficient way of handling terrain geometries utilizing data directly from DMA sources was felt to be needed. Consequently, the geometry module in the MORSE Monte Carlo radiation transport code was replaced by a terrain geometry module which not only permitted maintaining the full resolution of the digitized data but also considerably improved the speed of ray tracing in air/ground geometries.

The terrain geometry module accommodates single value surfaces which are described by a regular cartesian array of elevation points. The mesh sizes of the array may be different in the x and y directions. Elevations at interstitial points are determined by a linear interpolation procedure involving the four nearest mesh points. Local surface normal vectors are also calculated to permit treatment of the ground as an albedo scattering medium.

Modeling of the ground as a doubly differential albedo material permitted an additional improvement in the computing efficiency of the topographic calculations with virtually no loss in accuracy of the calculations. Both the terrain geometry and ground albedo scattering models were checked with conventional models and treatments and determined to be functioning properly.

4. RESULTS OF CALCULATIONS

In this section the results of the several calculations are presented. The presentation of results are subdivided into two major subsections, the effects of a dense forest, and the effects of topographic features. For the results of the effects of topographic features, the results are presented in the order of idealized valleys, idealized hills and real terrain calculations.

4.1 Forest Calculations

Figures 12 through 15 give the results of the discrete ordinates calculations of the dense forest model. The results are given as the ratio of the prompt personnel dose with and without the presence of the forest layer. This ratio can be interpreted as a transmission factor which can be applied to air/ground calculations to account for the presence of a dense forest. Each figure in the sequence shows the dose ratio as a function of horizontal ground range for a particular source height. Source heights range from .75 meters through 161.5 meters. Each figure shows the dose ratio for the three weapon spectra, which are representative of three tactical nuclear weapons.

4.2 Sensitivity Calculations

Sensitivity calculations were performed using a two dimensional sensitivity analysis program designated as SAIDOT (Sensitivity Analysis Instrument using Discrete Ordinate Transport) which has been developed at SAI. The purpose of these calculations were to provide additional insight into the effects of a forest cover on the radiation environments from tactical nuclear weapons. Specifically, these calculations indicate how the effects of the forest cover might change with density of the forest layer and composition of materials.

Sensitivity calculations were performed for a tissue response and the weapon type A at a burst height of 36.5 meters. Table X summarizes the results of these calculations. The sensitivities are dimensionless and give the fractional change in the radiation dose due to the indicated addition of materials which reflect a change in cross sections.

4.3 Topographic Calculations

The results of the Monte Carlo calculations for the several topographic problems are presented as plots of dose to personnel per source particle versus

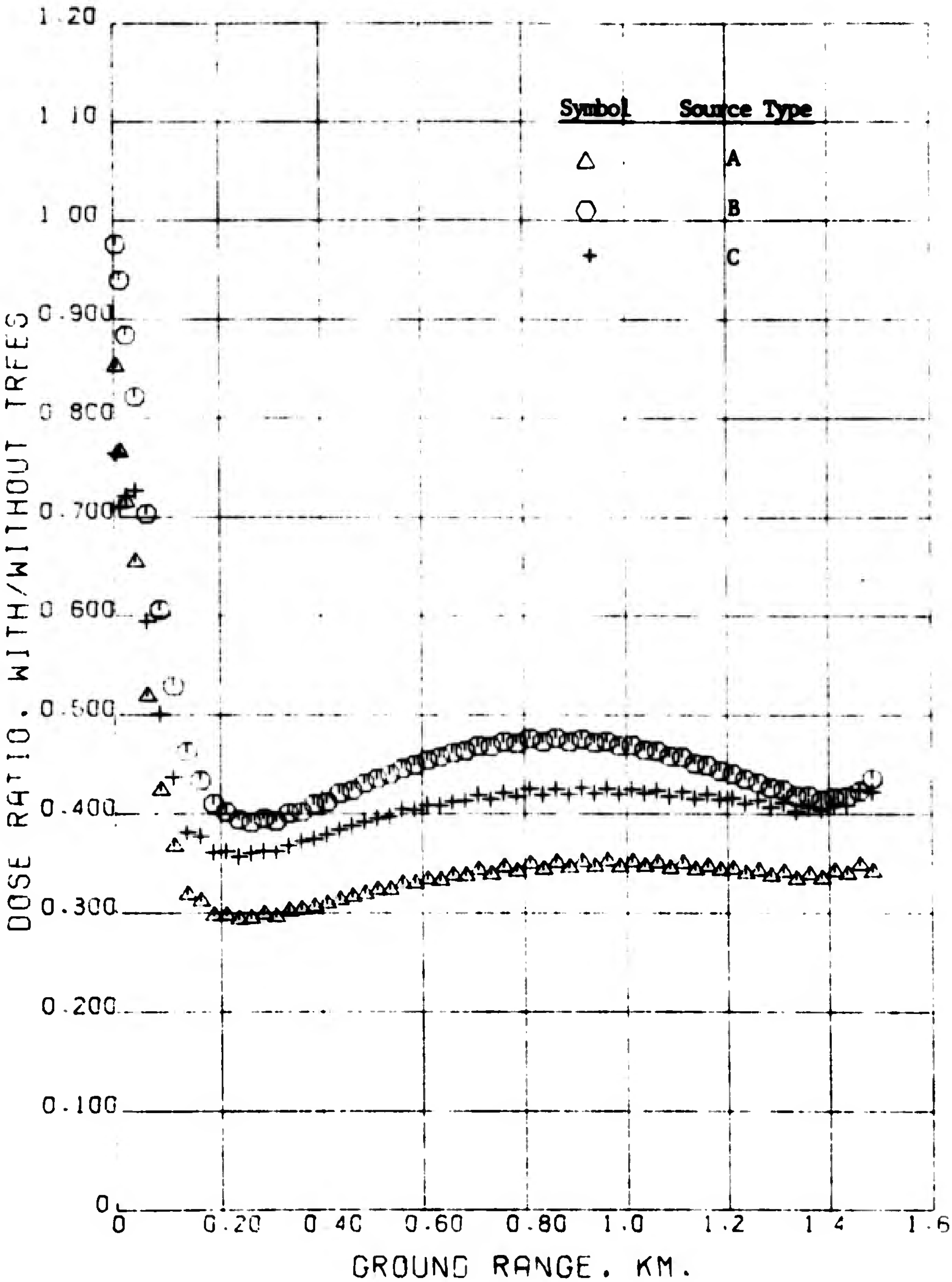


Figure 12. Forest transmission factors for three weapon sources for a source height of .75 meters.

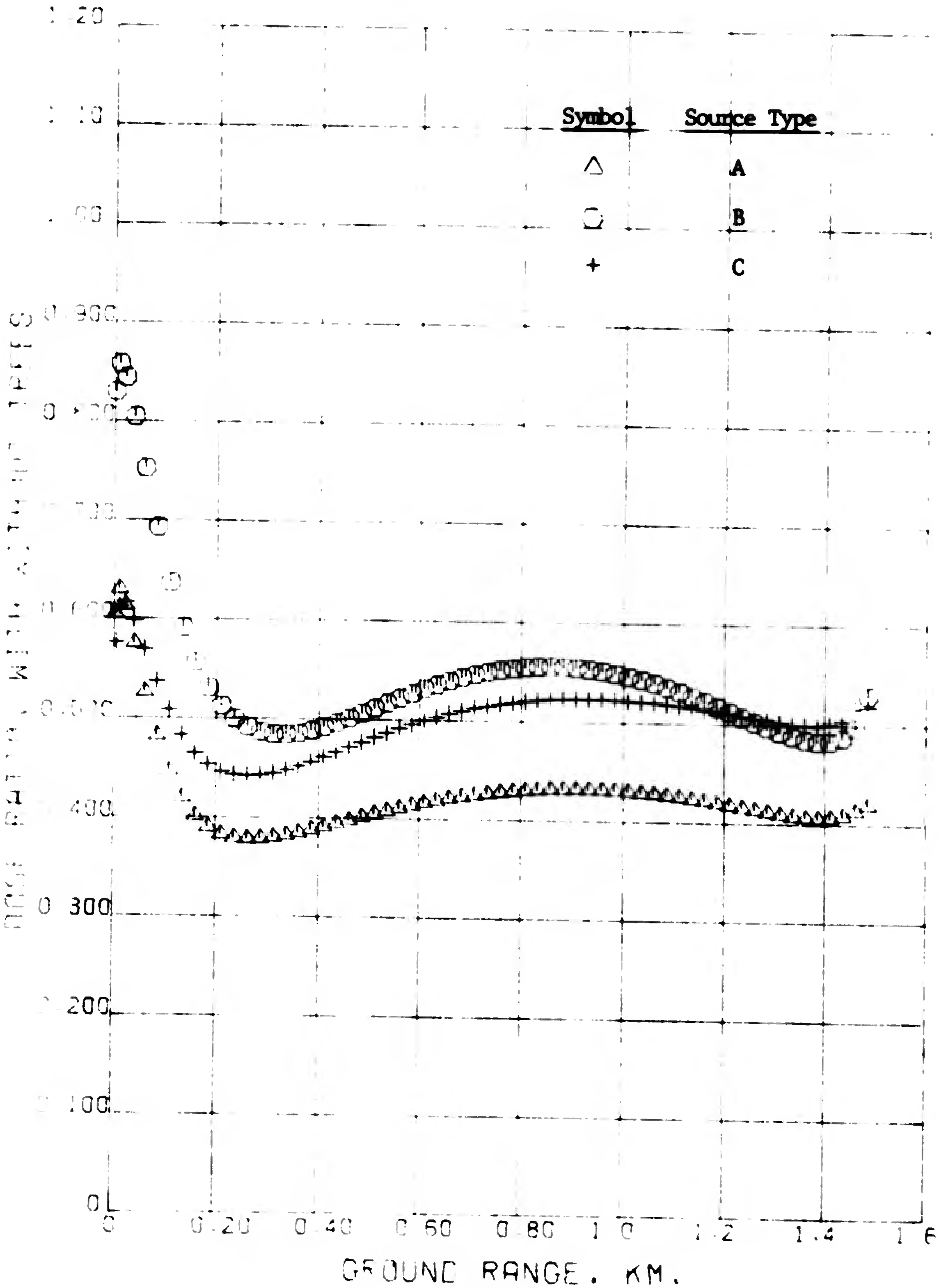


Figure 13. Forest transmission factors for three weapon sources for a source height of 36.5 meters.

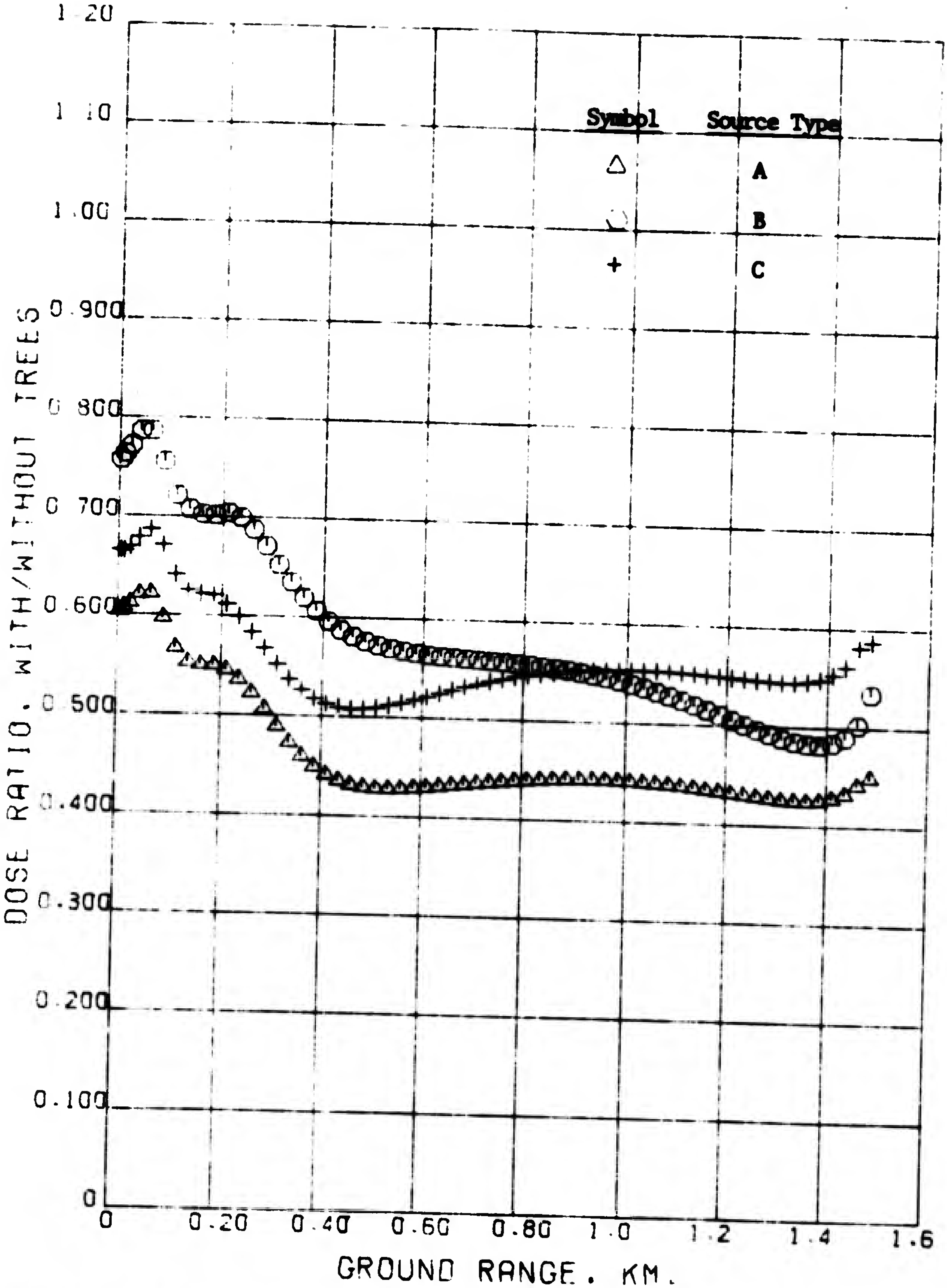


Figure 14. Forest transmission factors for three weapon sources for a source height of 111.5 meters.

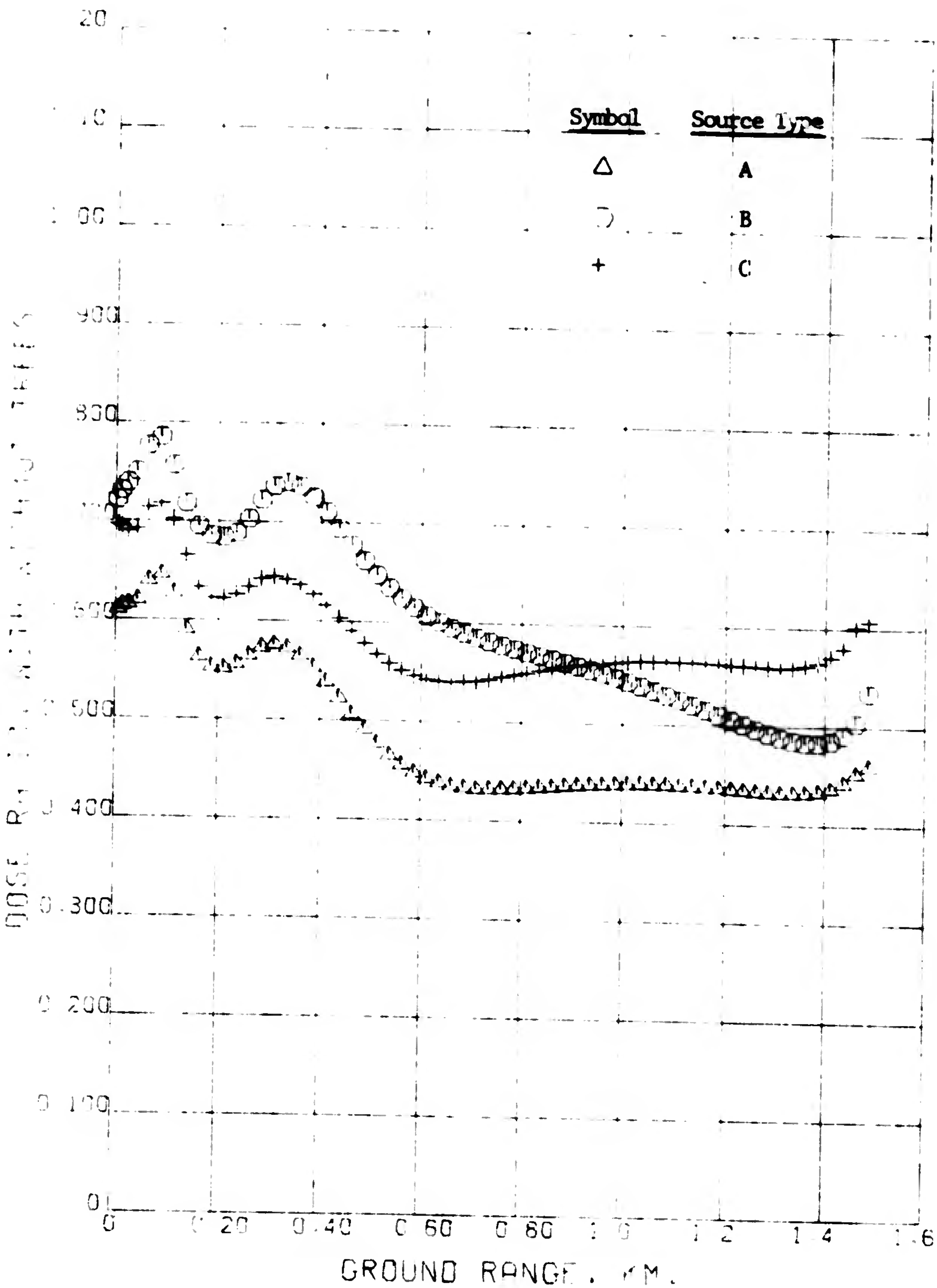


Figure 15. Forest transmission factors for three weapon sources for a source height of 161.5 meters.

Table X. Summary of sensitivity results for materials in a forest cover.

Element	Density Atoms/ b · cm	Sensitivity, $\frac{\Delta D}{D}$ Neutron Cross Section	Gamma Ray Cross Section	Total
N	7.2 (-8)	-4.4 (-5)	-8.3 (-6)	-5.2 (-5)
O	1.373 (-5)	-2.2 (-3)	-1.8 (-3)	-4.0 (-3)
H	3.0864(-5)	-3.1 (-1)	-4.8 (-4)	-3.1 (-1)
C	2.116 (-5)	-1.2 (-2)	-2.1 (-3)	-1.4 (-2)
Sum		-3.3 (-1)	-4.4 (-3)	-3.3 (-1)

horizontal ground range. Horizontal ground range is the distance between two points that one would measure on a map, and does not reflect difference in elevation between the two points. For each problem two figures are presented, one for free field dose to personnel and the other for dose to personnel shielded by light armor. For each figure two plots are given. The smooth line in each case is the plot of the appropriate flat earth results from reference 5, and is shown to facilitate a visual assessment of the effects of the particular terrain description. The histogram gives the results of the Monte Carlo calculations. Vertical bars are drawn to illustrate the standard deviation of the Monte Carlo results. In general the fractional standard deviation of the Monte Carlo results was 25% at a ground range of 1 kilometer and are significantly larger at larger ground ranges, and significantly smaller at smaller ground ranges.

The first two figures, Figures 16 and 17, are the results of the Monte Carlo calculations for flat ground.

The results for the idealized terrain problems are given in Figures 18 through 47. Table VIII in Section 3 gives an index to the problem descriptions and results.

The results of the terrain calculations are given in two forms. Figures 48 through 53 give the results of the real terrain problems averaged over annular areas. To indicate the asymmetry of the real terrain results, the free field and shielded tissue doses are tabulated for a 200 by 200 meter cartesian grid of north and east horizontal range from ground zero. These results are given in Tables XI through XVI.

4.4 Air/Ground/Water Calculations

Figure 54 shows the prompt tissue dose vs horizontal ground range for the air/ground calculation with an annulus of water between 200 and 300 meters and for a source height of 40 meters. The smooth line gives the corresponding tissue dose vs ground range for air/ground only.

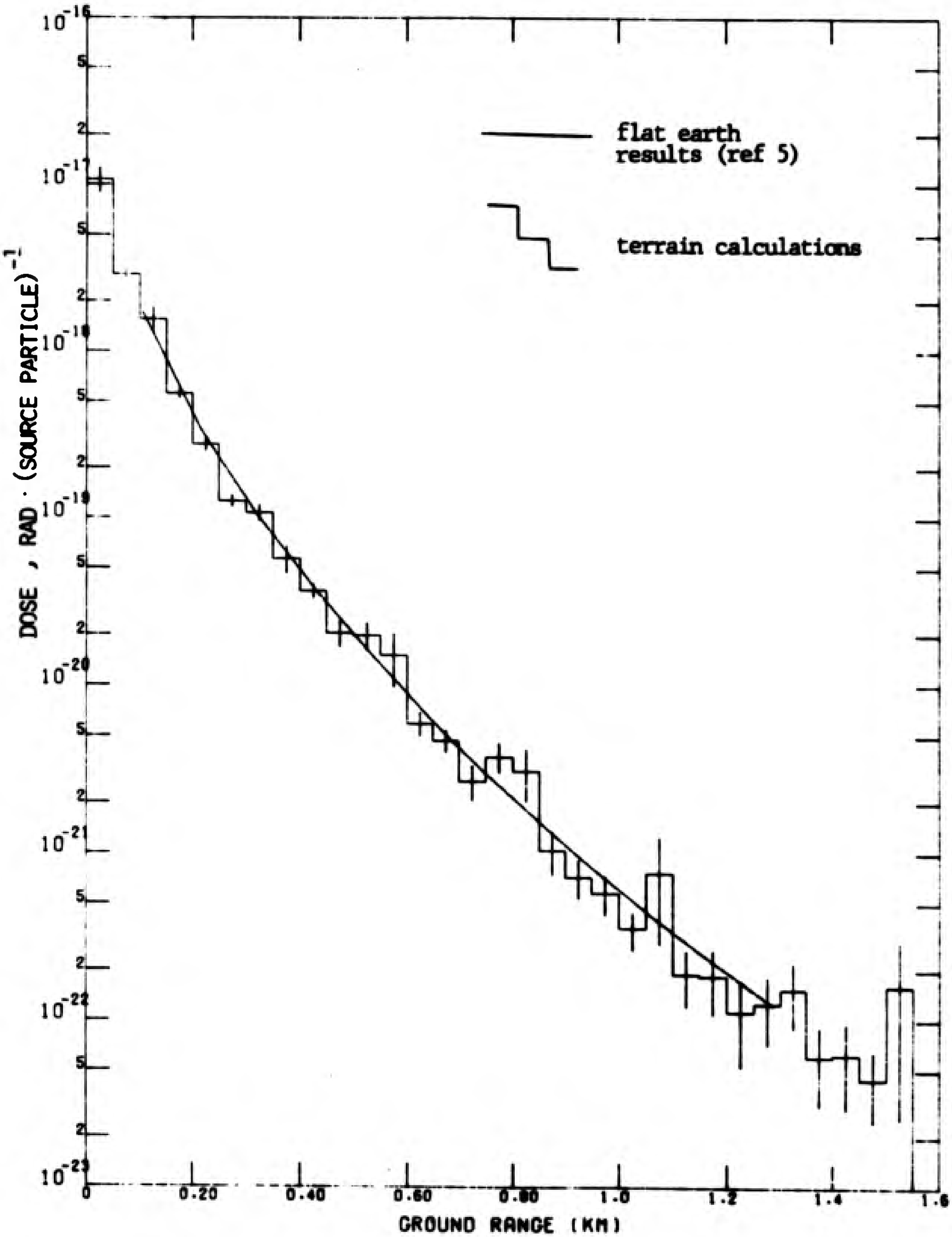


Figure 16. Prompt tissue dose versus ground range: flat ground.

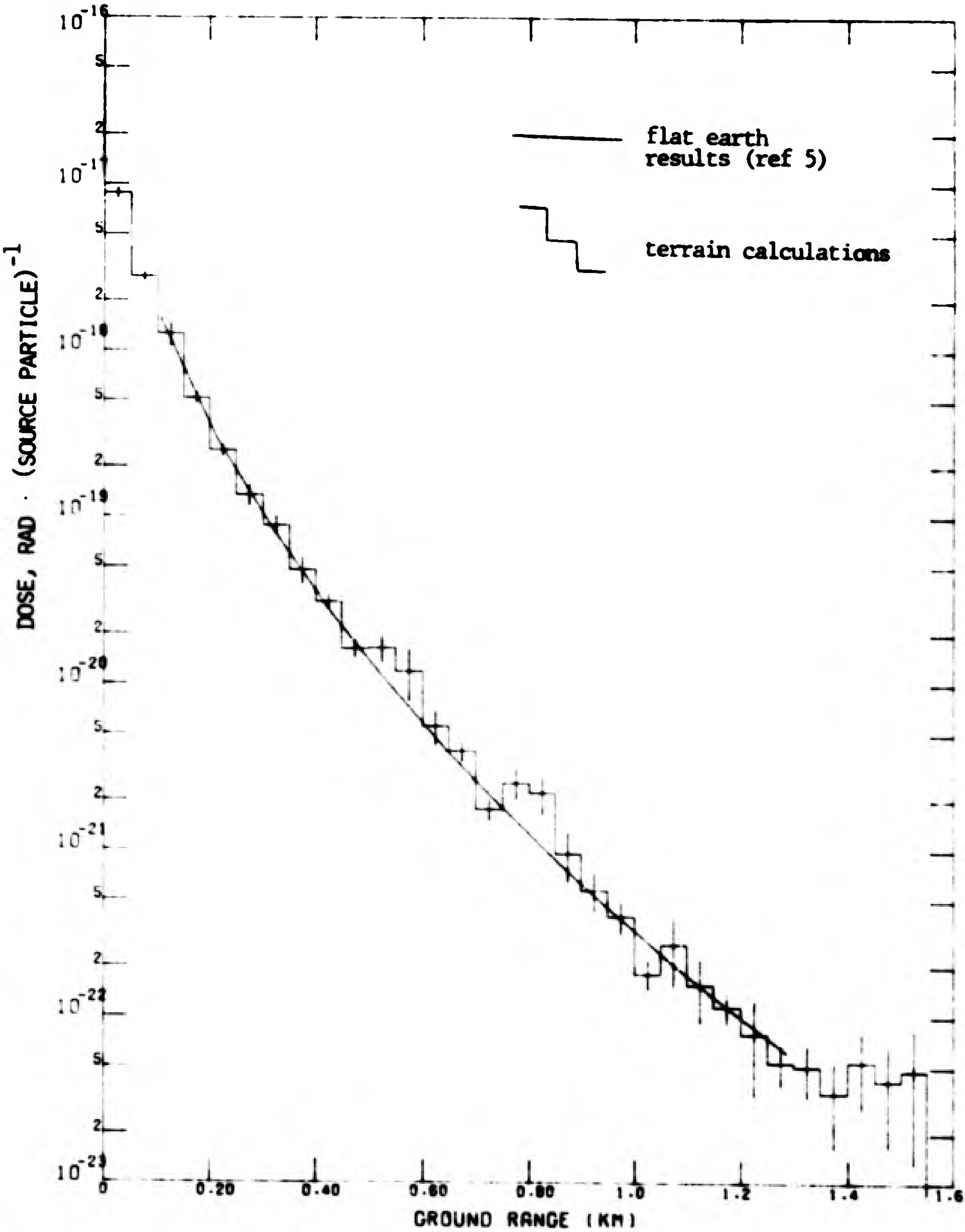


Figure 17. Prompt armor shielded tissue dose versus ground range: flat ground.

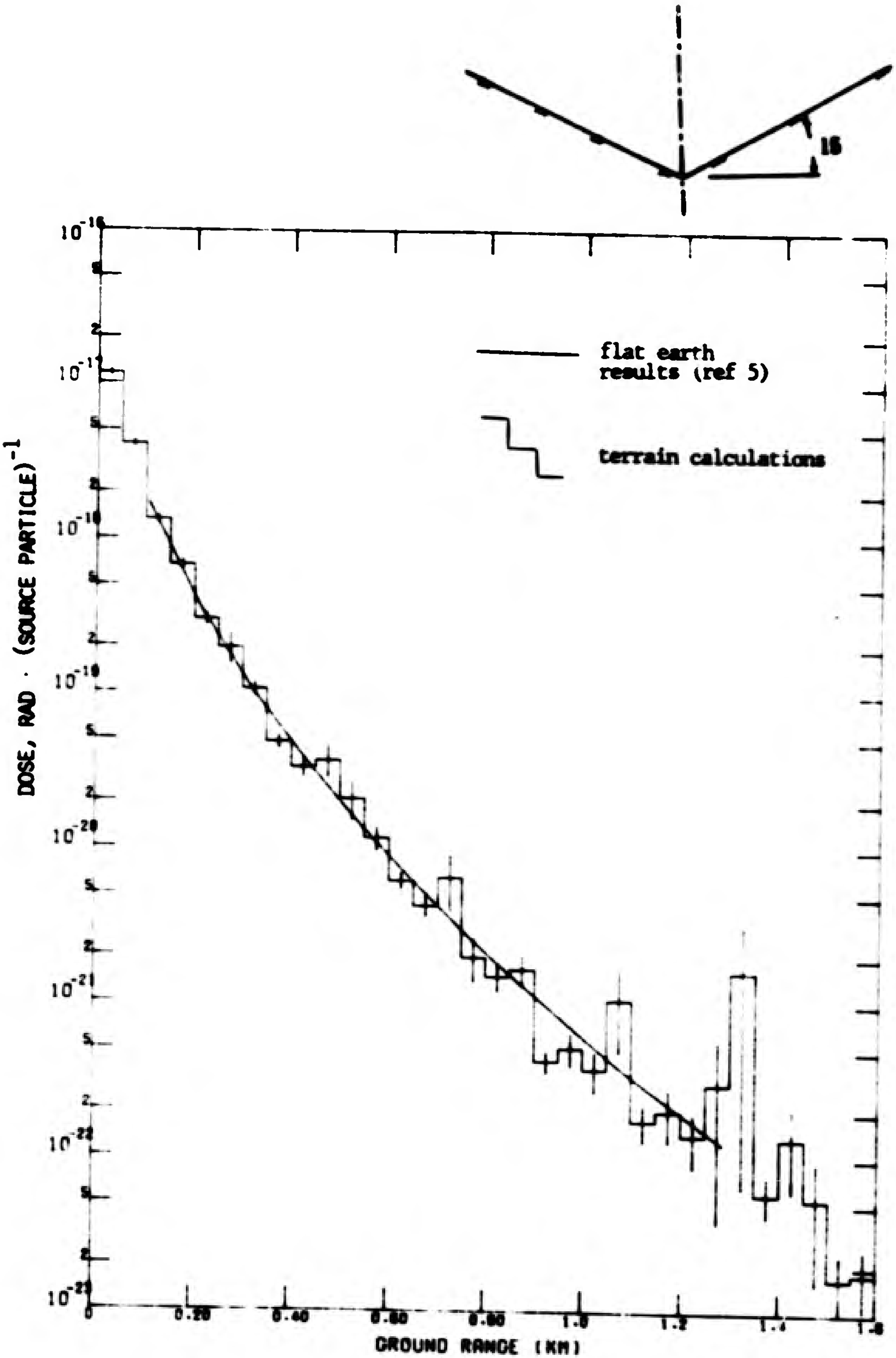


Figure 18. Prompt tissue dose versus ground range: valley problem 1, 15° slope, 40 m HOB, weapon type A.

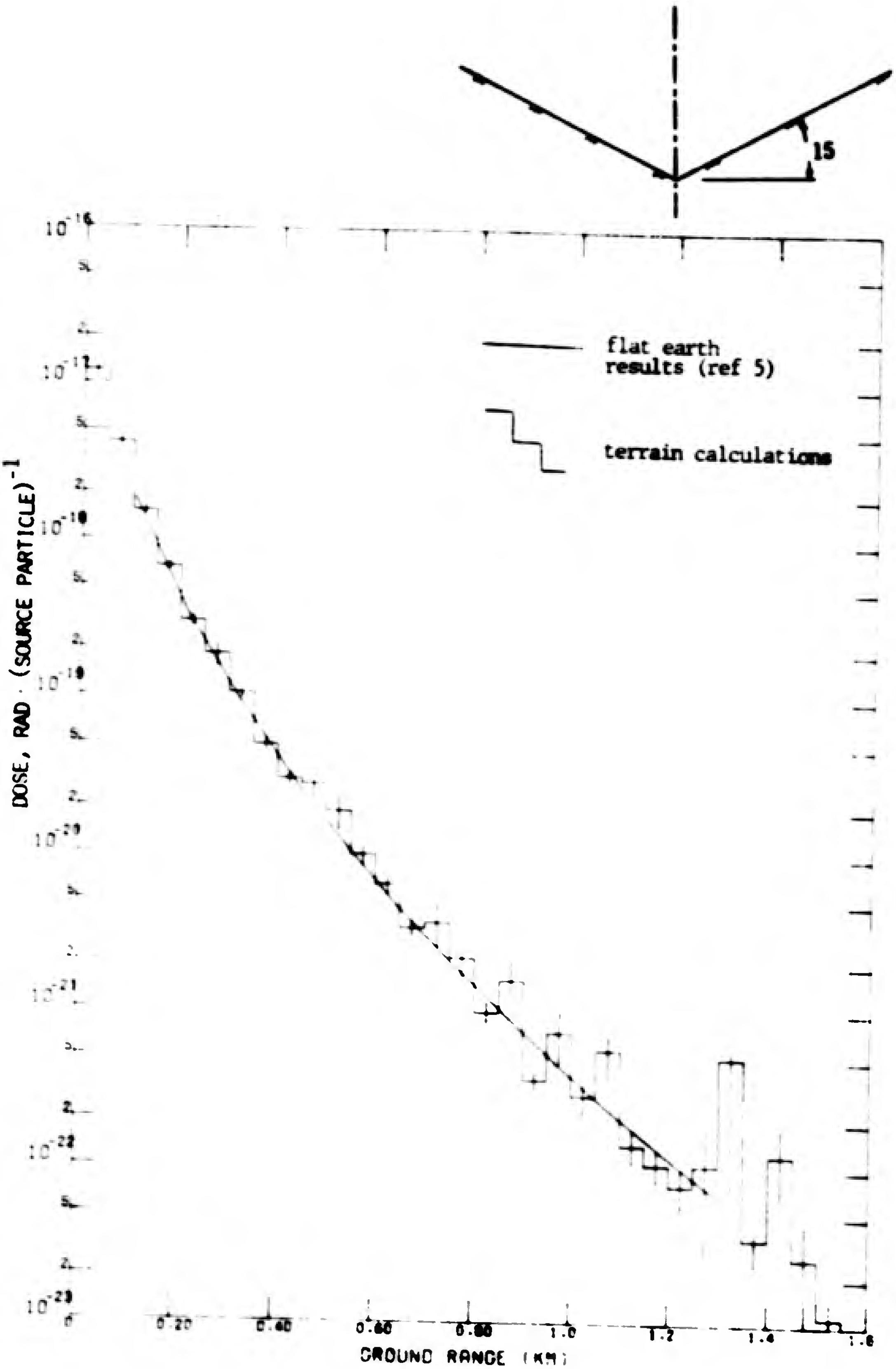


Figure 19. Prompt armor shielded tissue dose versus ground range: valley problem 1, 15° slope, 40 m HOB, weapon type A.

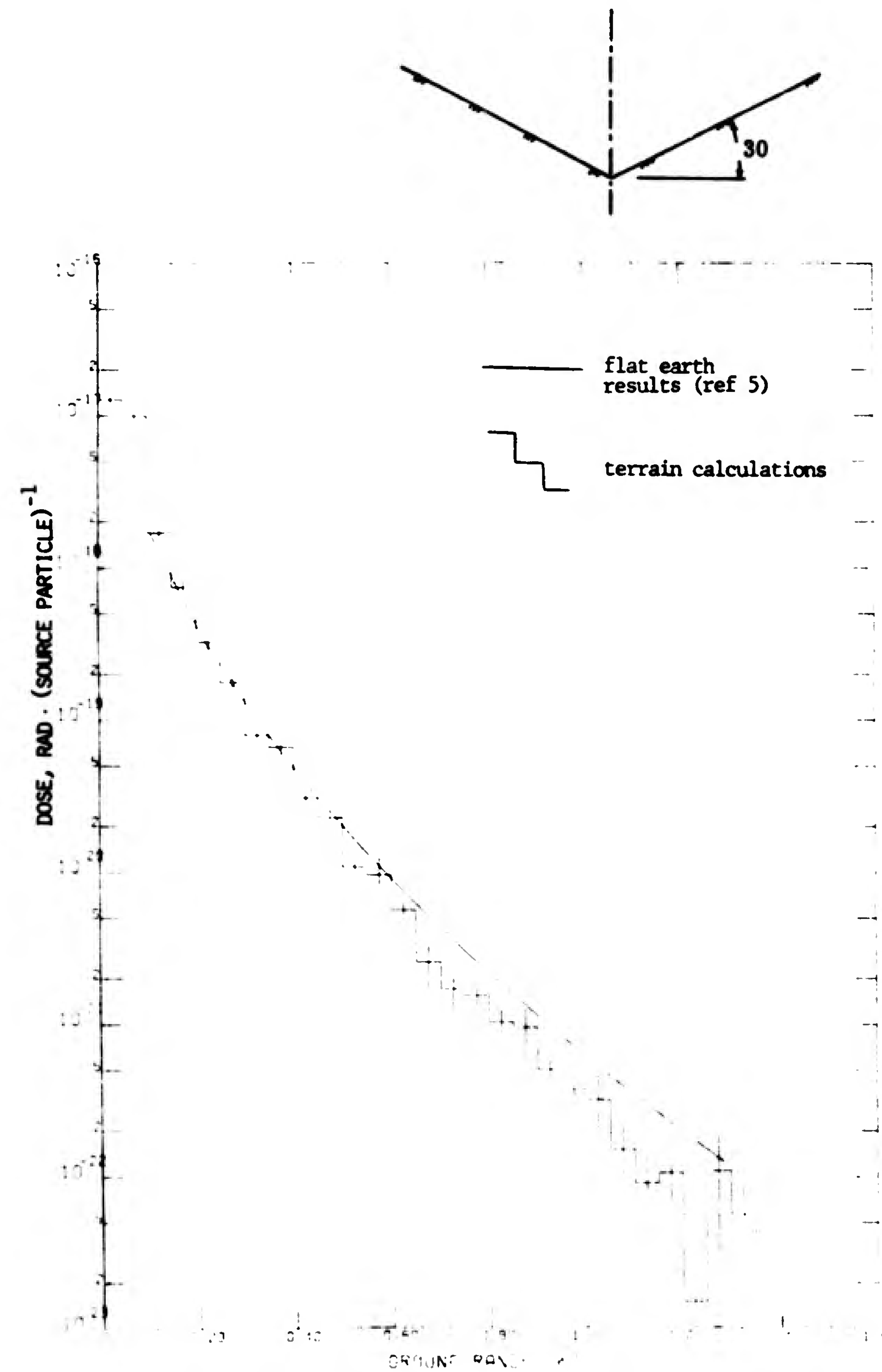


Figure 20. Prompt tissue dose versus ground range: valley problem 2, 30° slope, 40 m HOB, weapon type A.

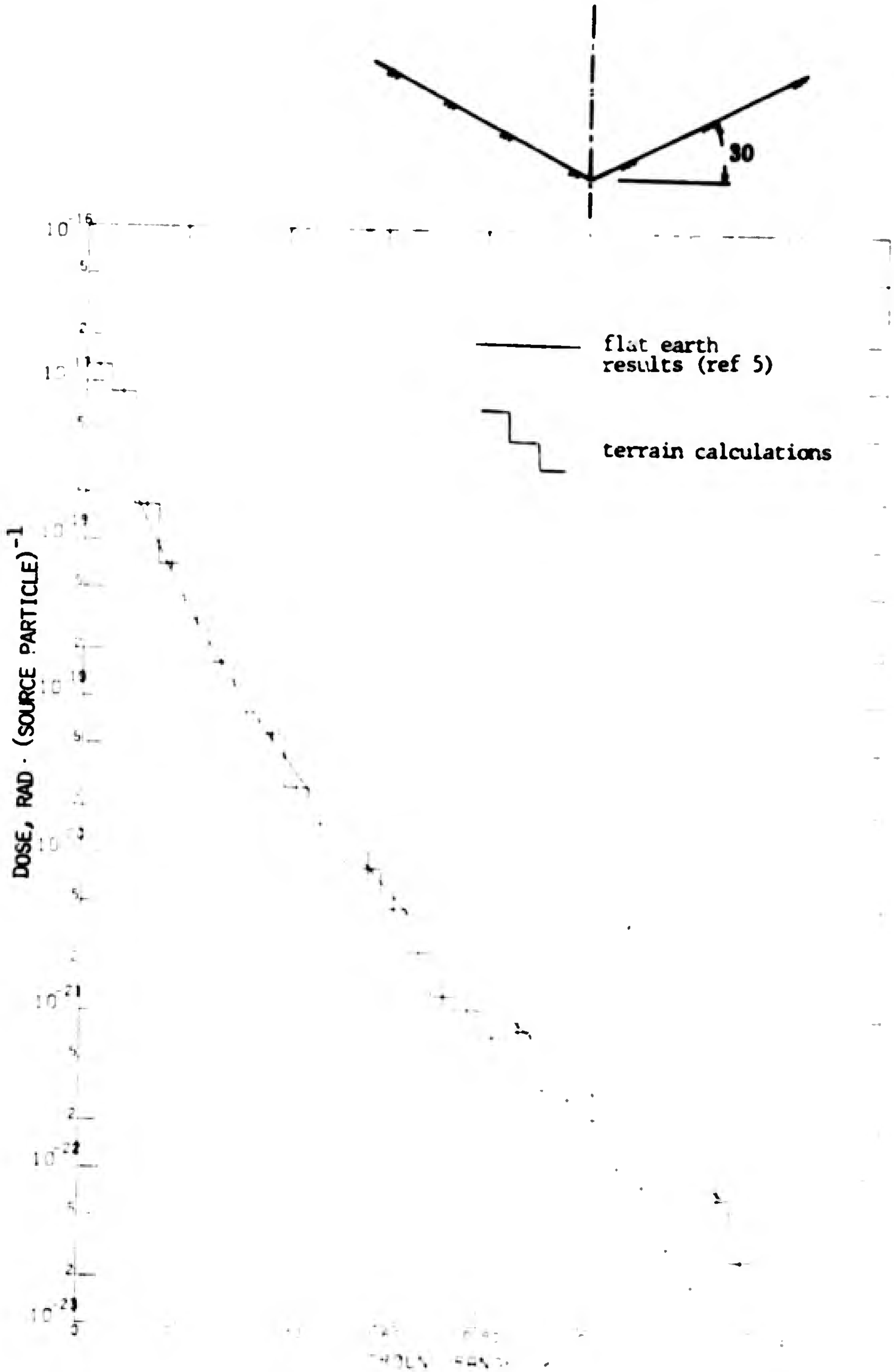


Figure 21. Prompt armor shielded tissue dose versus ground range: valley problem 2, 30° slope, 40 m HOB, weapon type A.

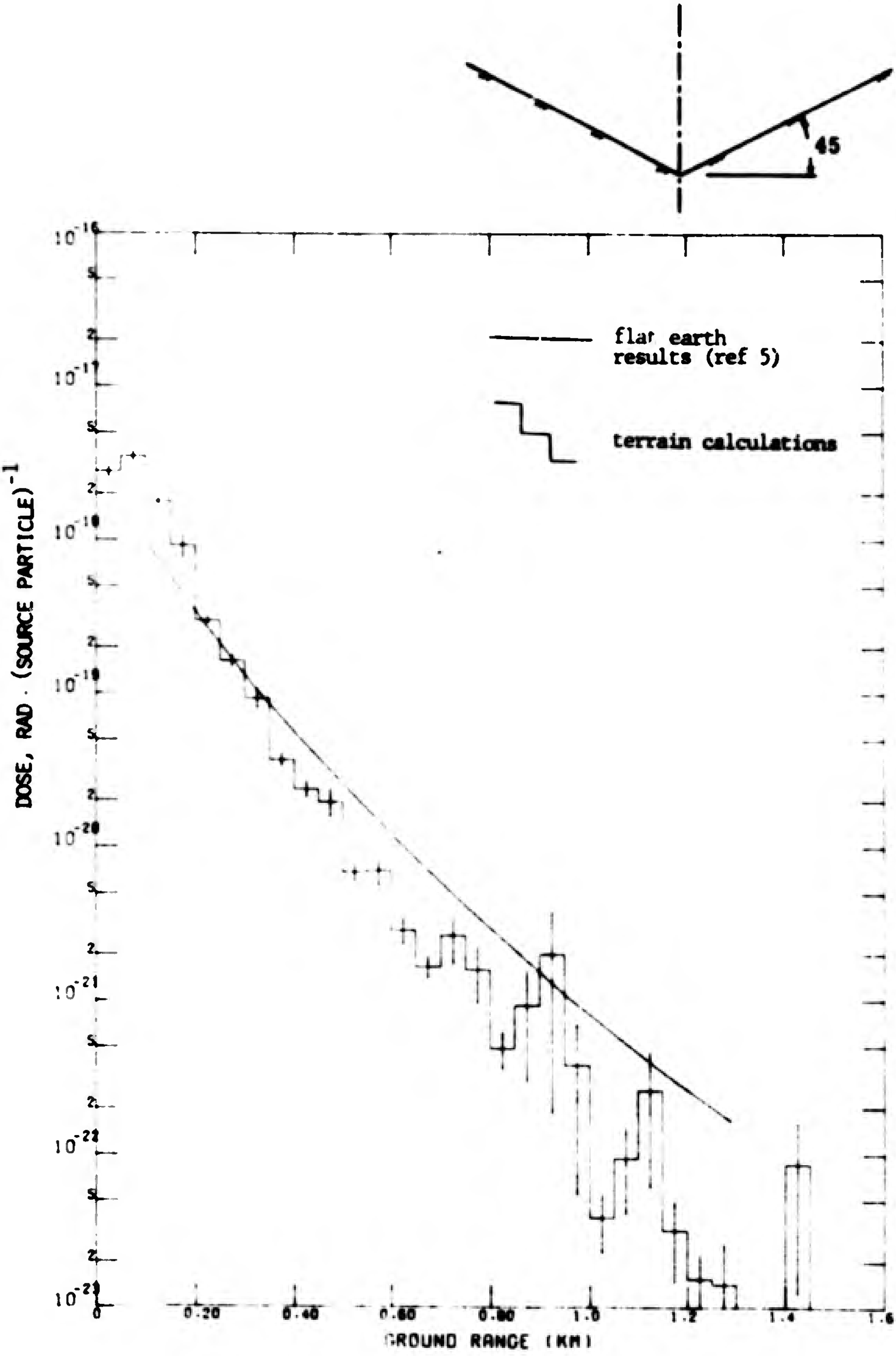


Figure 22. Prompt tissue dose versus ground range: valley problem 3, 45° slope, 130 m HOB, weapon type A.

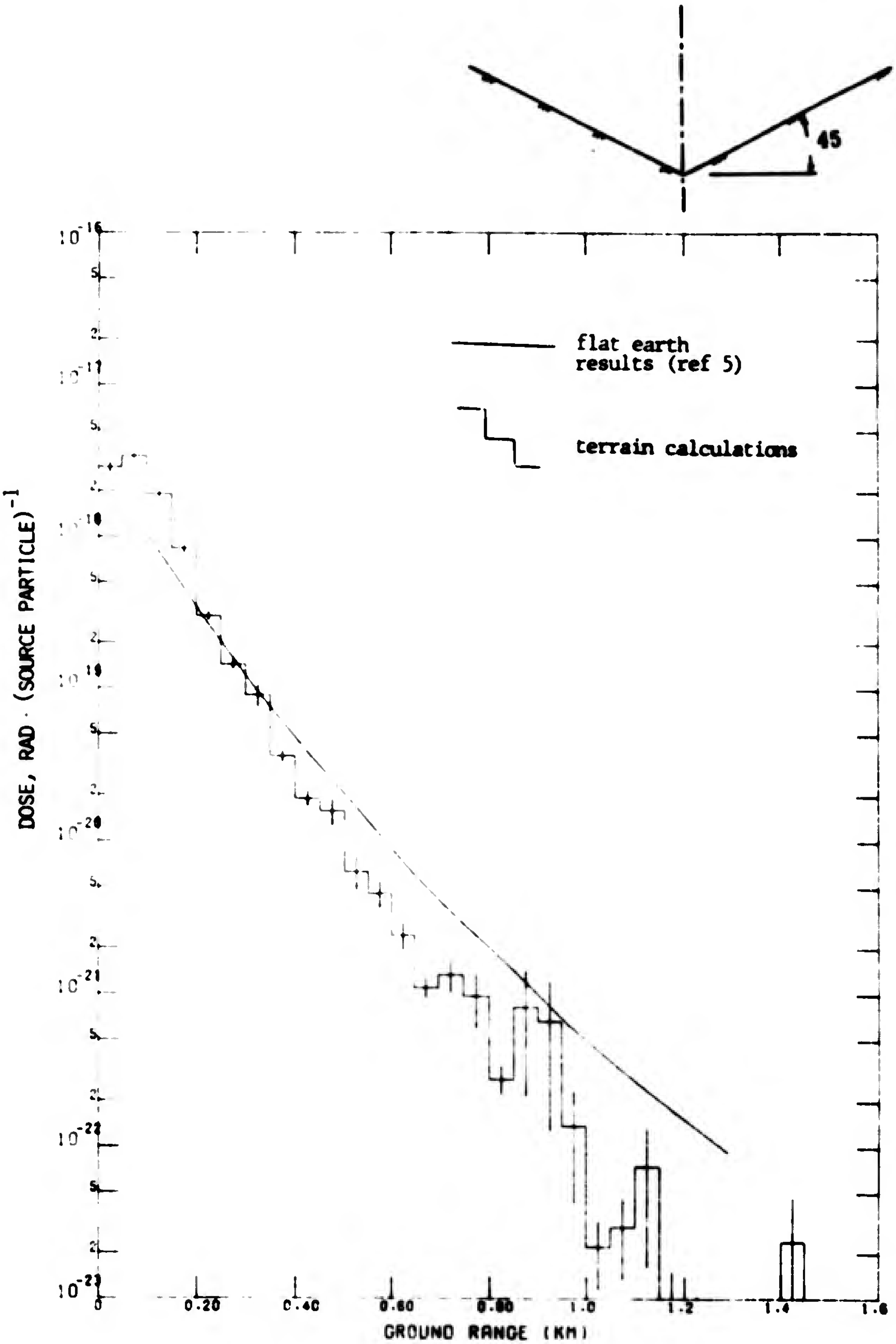


Figure 23. Prompt armor shielded tissue dose versus ground range: valley problem 3, 45° slope, 130 m HOB, weapon type A.

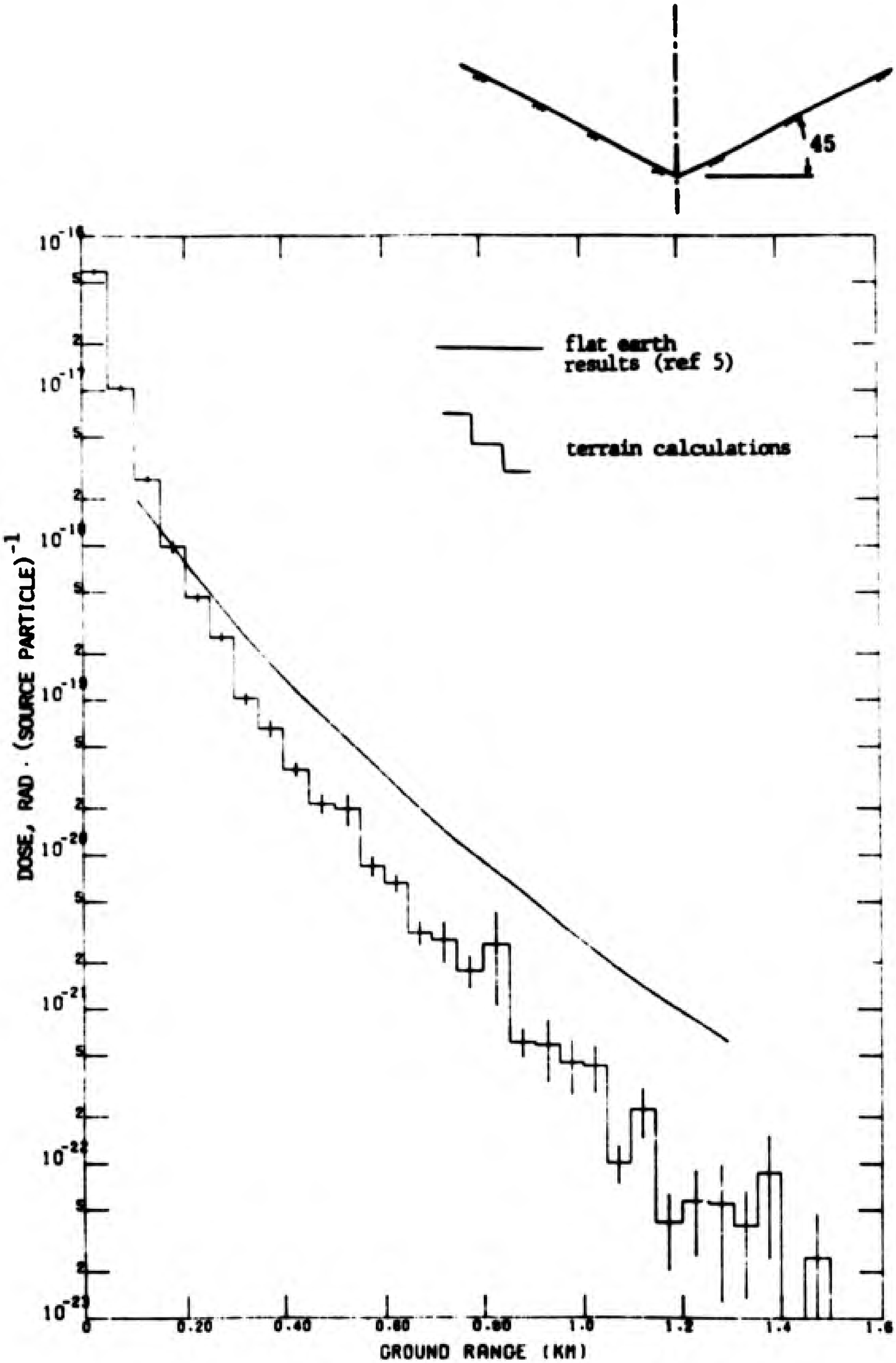


Figure 24. Prompt tissue dose versus ground range: valley problem 4, 45° slope, 130 m HOB, weapon type B.

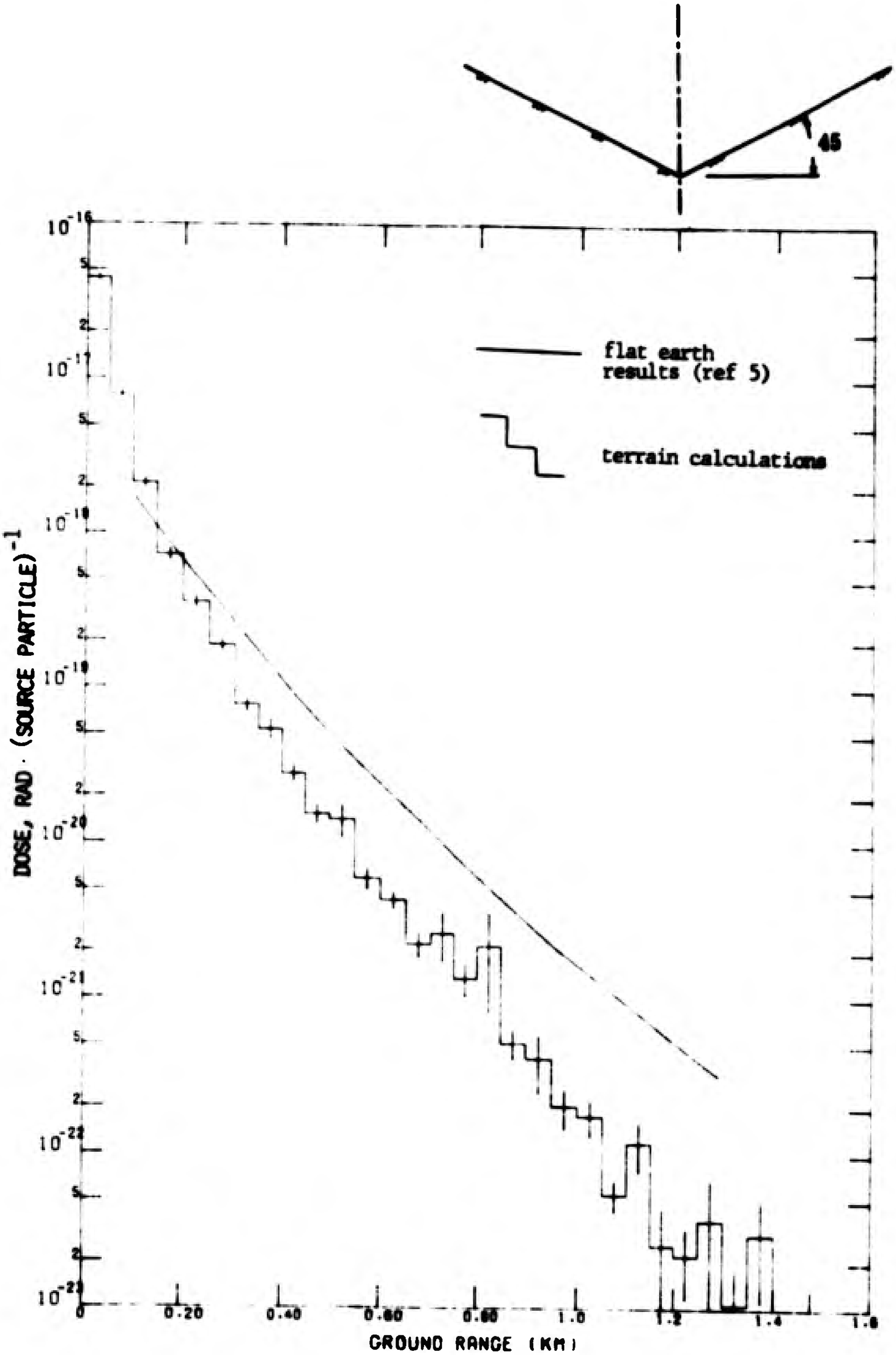


Figure 25. Prompt armor shielded tissue dose versus ground range: valley problem 4, 45° slope, 130 m HOB, weapon type B.

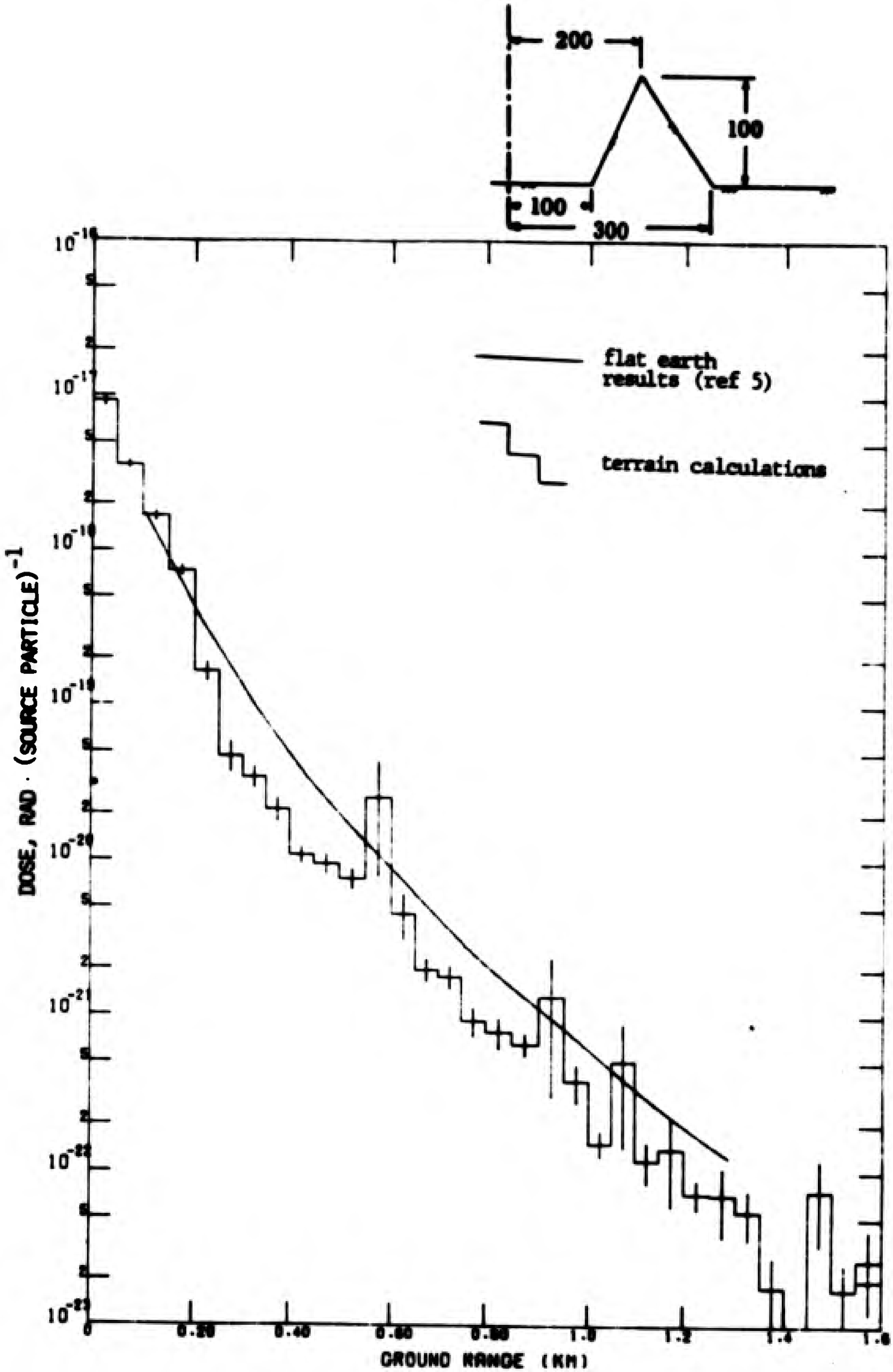


Figure 26. Prompt tissue dose versus ground range: hill problem 1, 100 m hill, weapon type A.

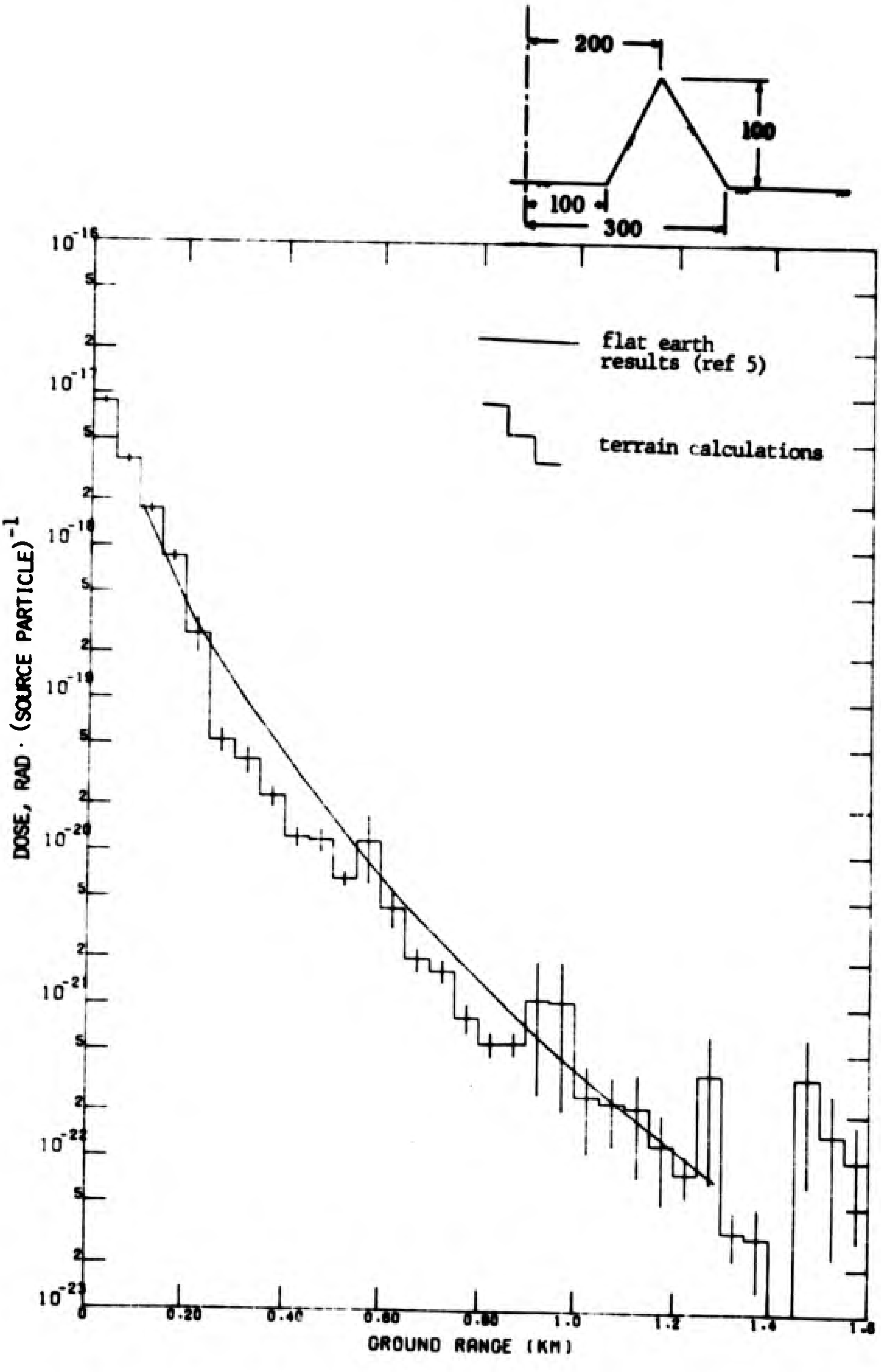


Figure 27. Prompt armor shielded tissue dose versus ground range: hill problem 1, 100 m hill, weapon type A.

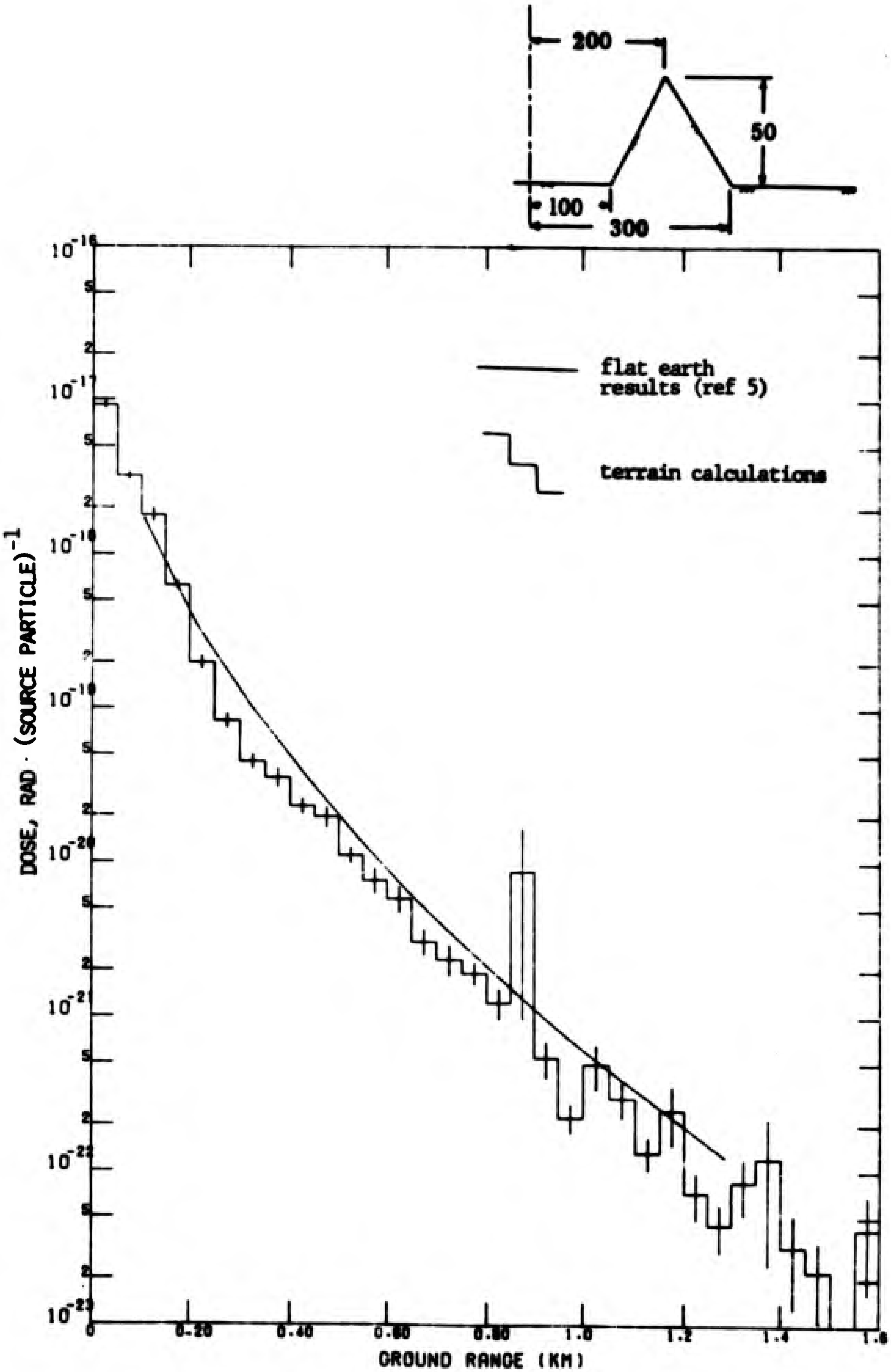


Figure 28. Prompt tissue dose versus ground range: hill problem 2, 50 m hill, weapon type A.

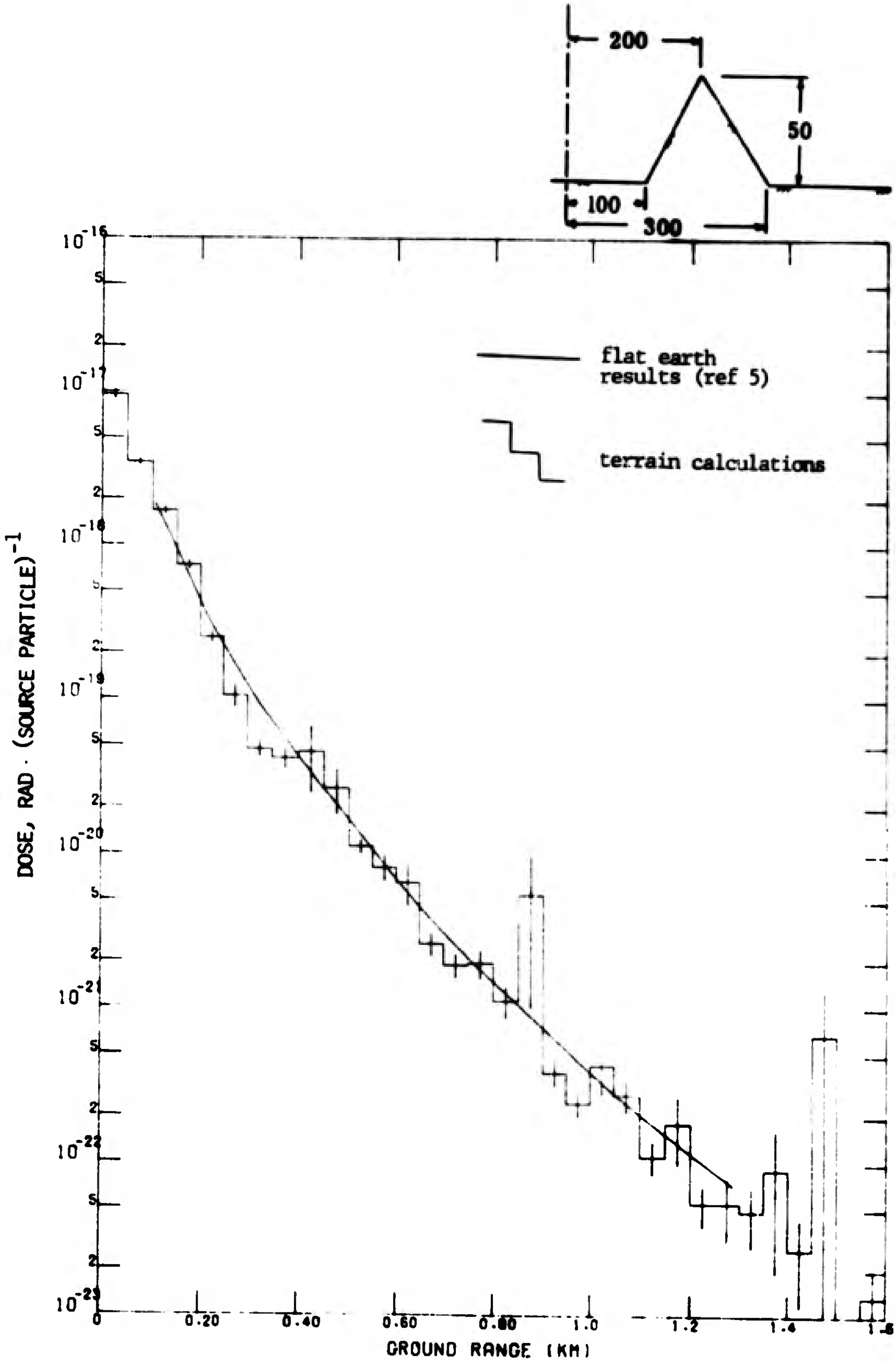


Figure 29. Prompt armor shielded tissue dose versus ground range: hill problem 2, 50 m hill, weapon type A.

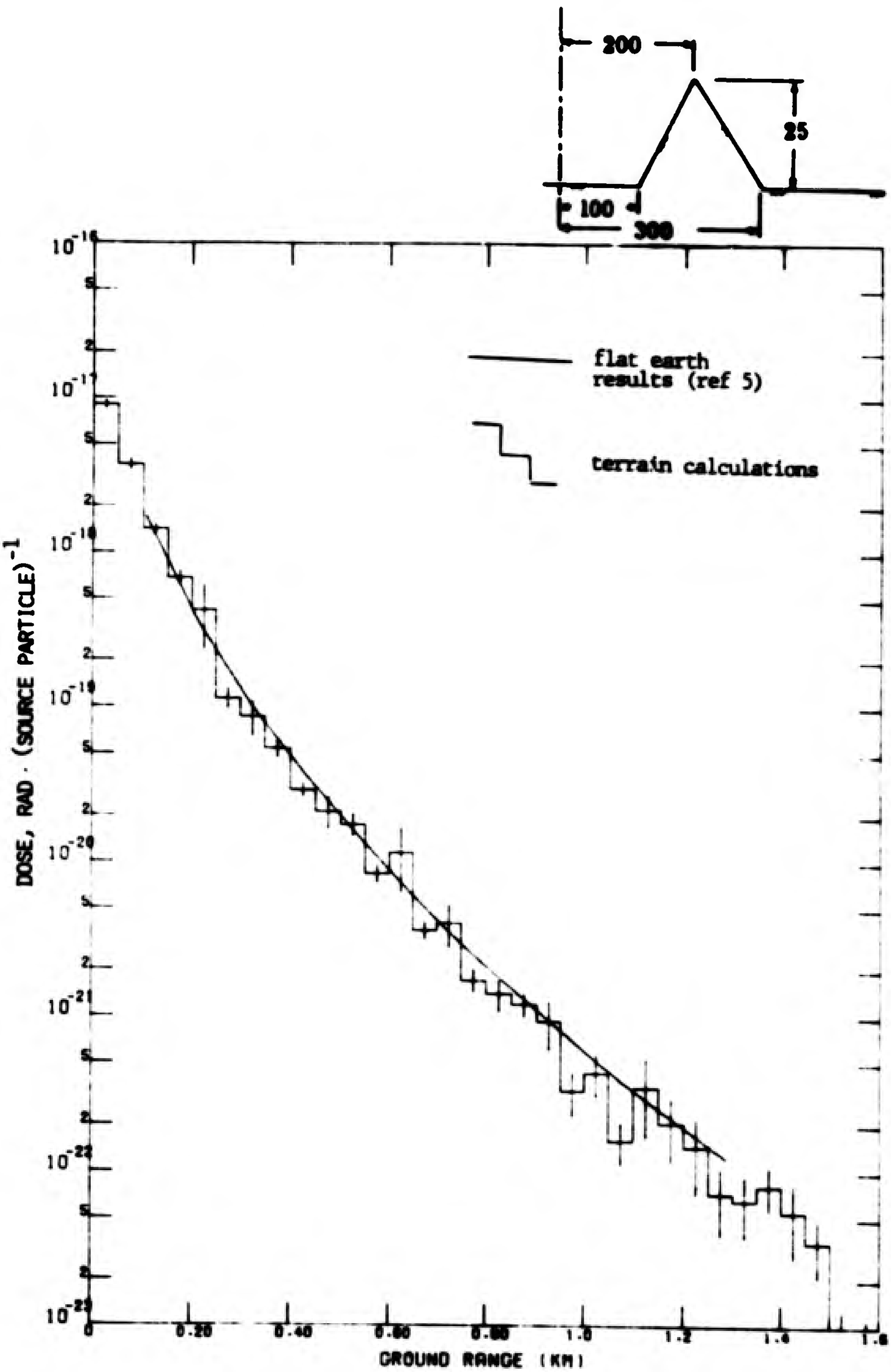


Figure 30. Prompt tissue dose versus ground range: hill problem 3, 25 m hill, weapon type A.

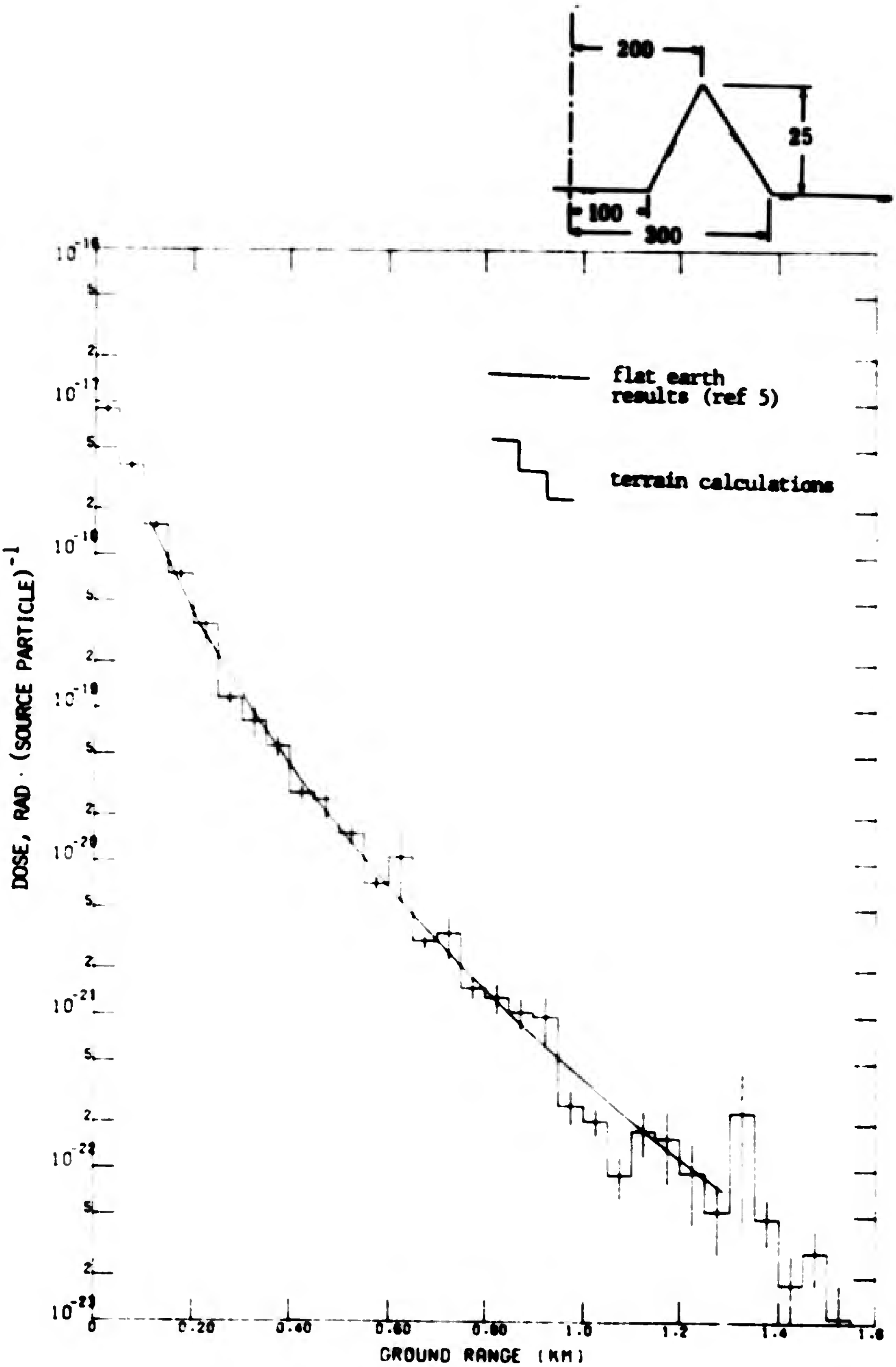


Figure 31. Prompt armor shielded tissue dose versus ground range: hill problem 3, 25 m hill, weapon type A.

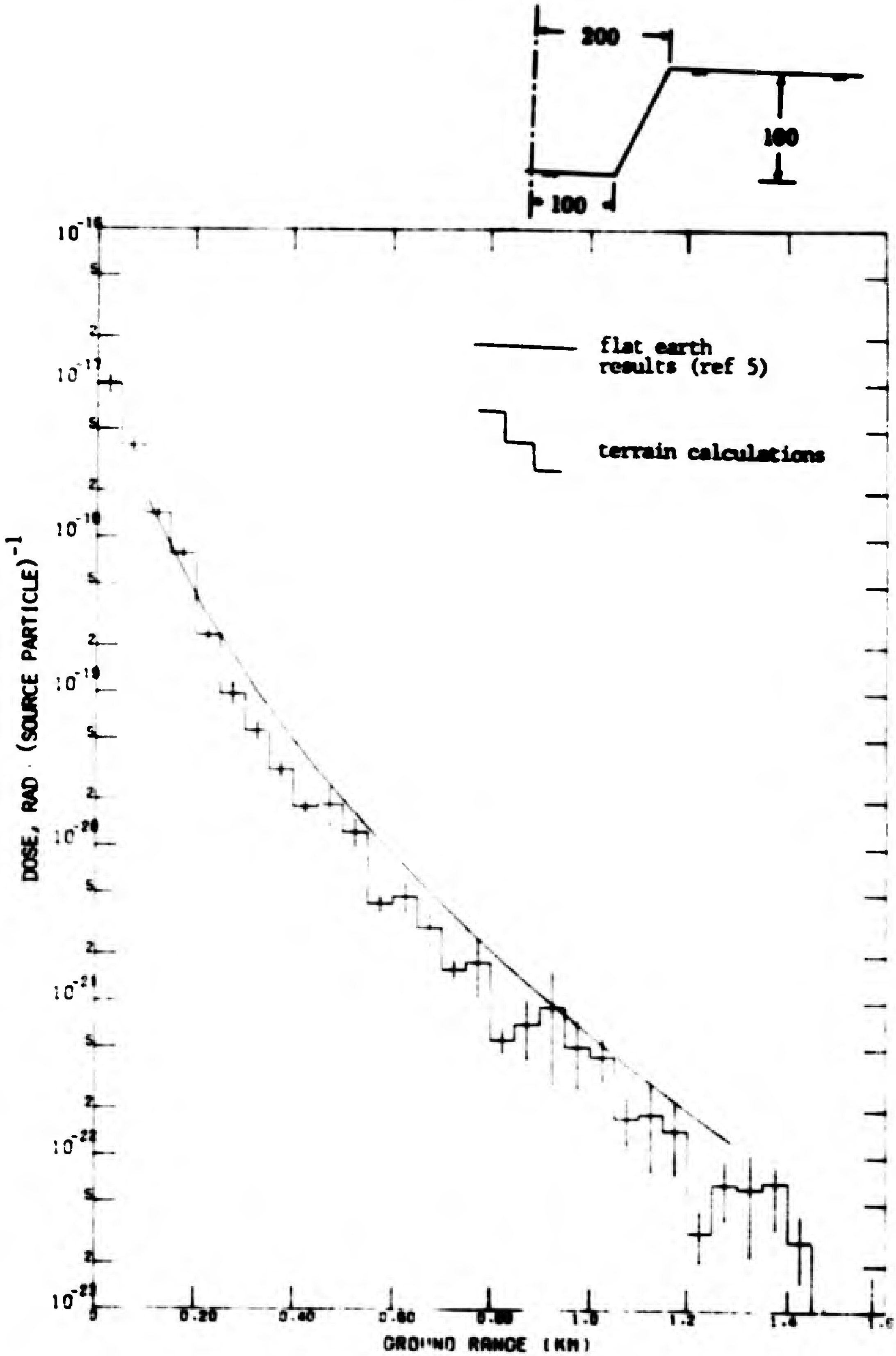


Figure 32. Prompt tissue dose versus ground range: hill problem 4, 100 m rise to plateau, weapon type A.

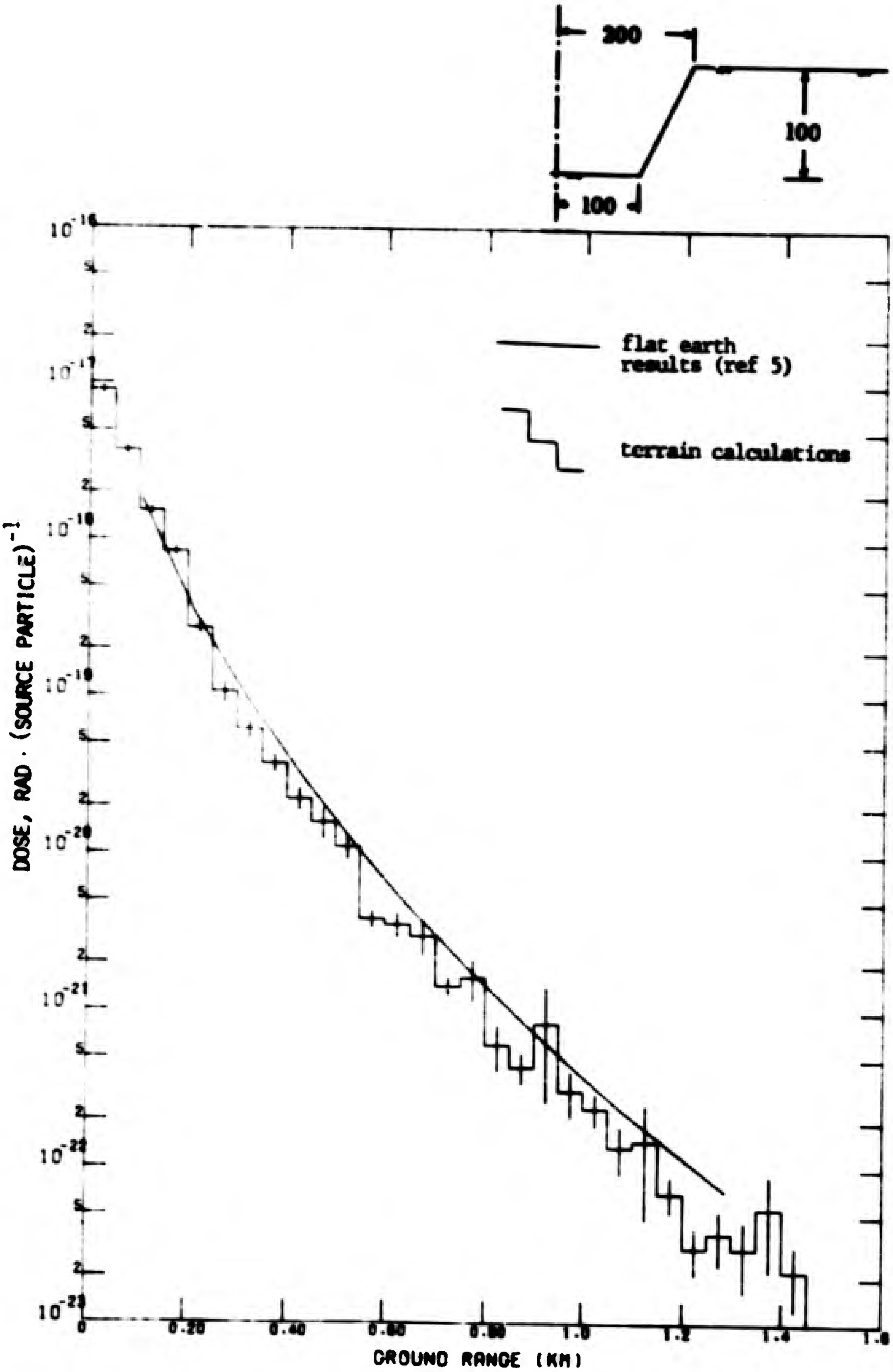


Figure 33. Prompt armor shielded tissue dose versus ground range: hill problem 4, 100 m rise to plateau, weapon type A.

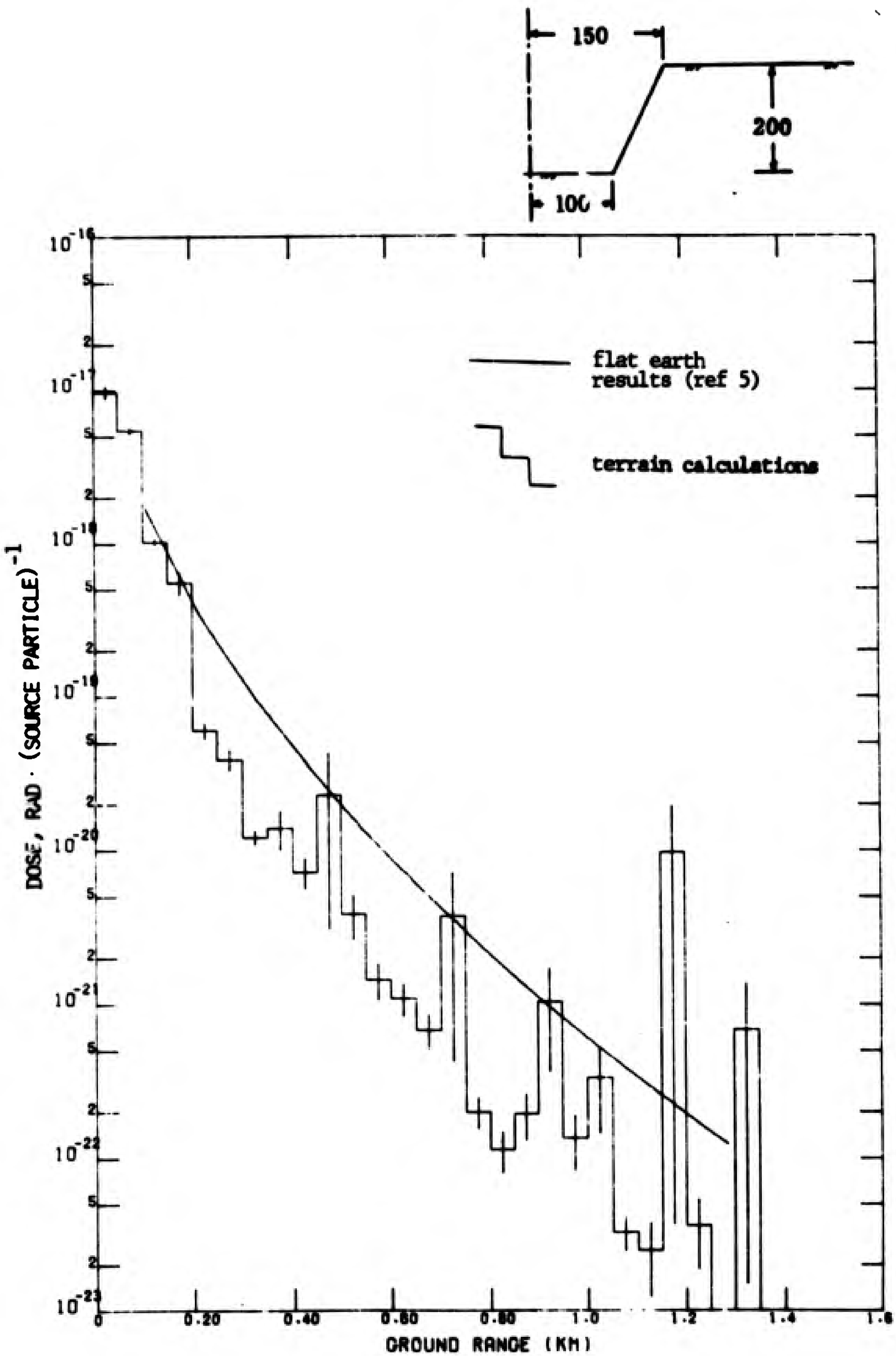


Figure 34. Prompt tissue dose versus ground range: hill problem 5, 200 m rise to plateau, weapon type A.

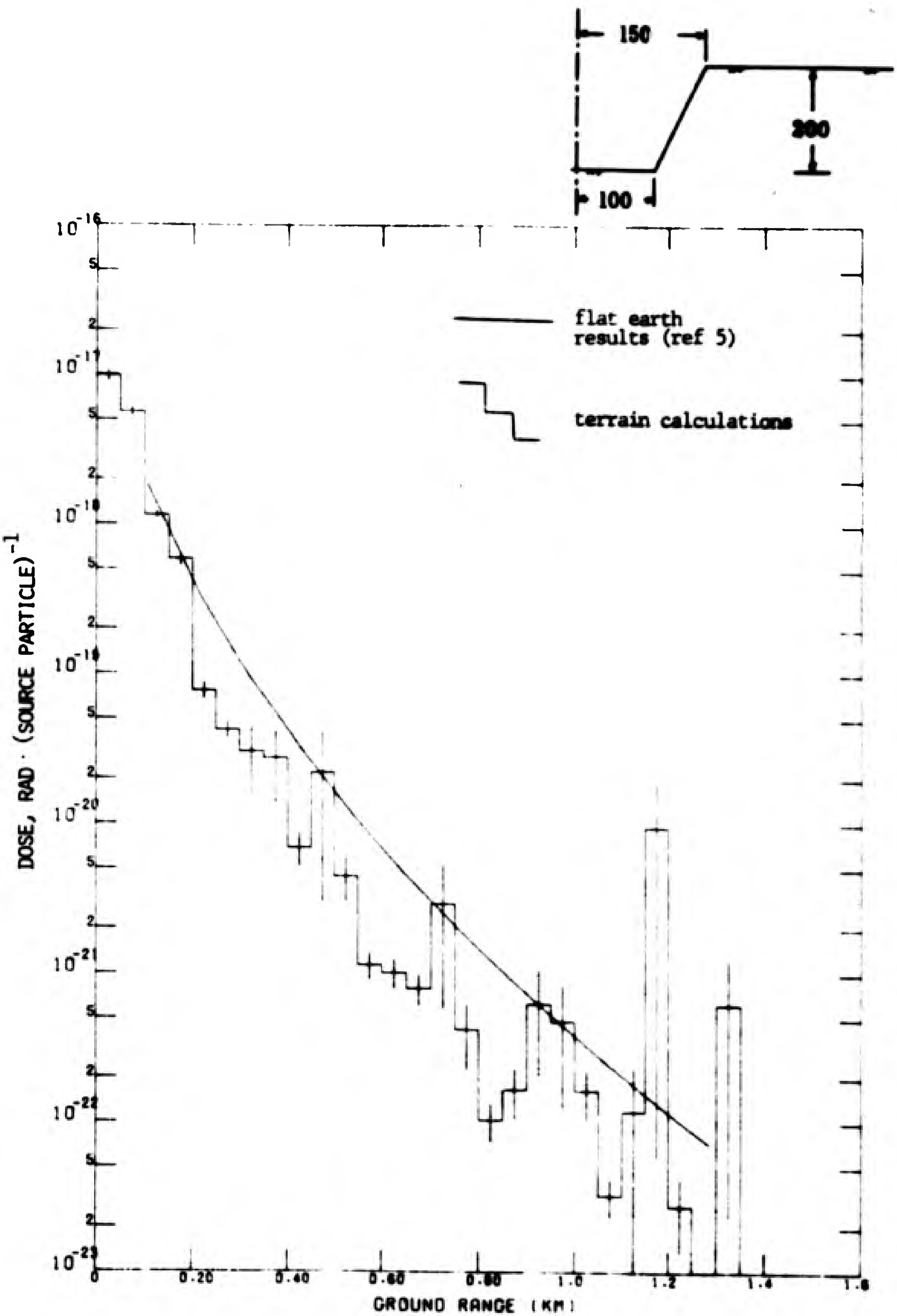


Figure 35. Prompt armor shielded tissue dose versus ground range: hill problem 5, 200 m rise to plateau, weapon type A.

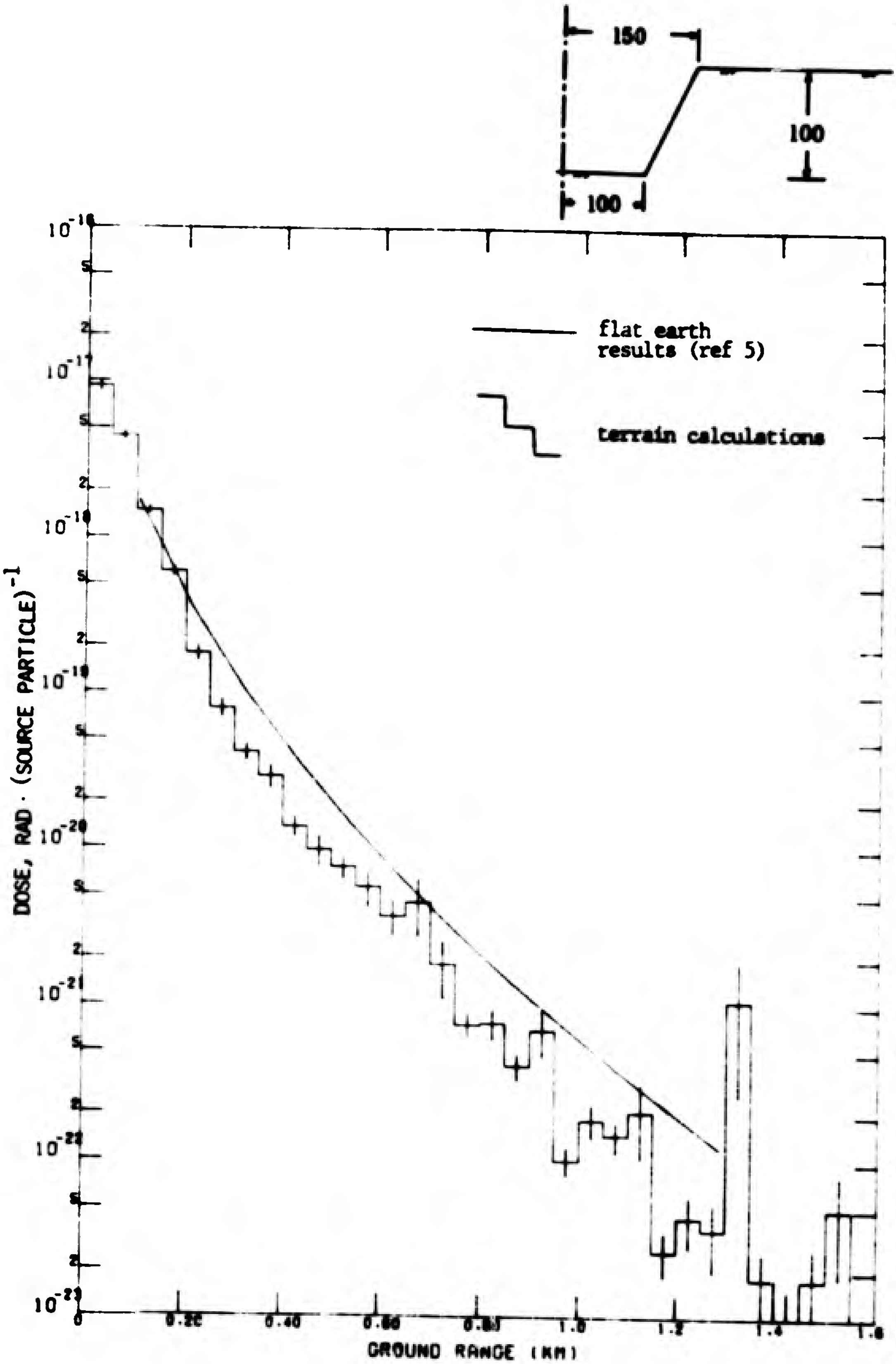


Figure 3· . Prompt tissue dose versus ground range: hill problem · , 100 m steep rise to plateau, weapon type A.

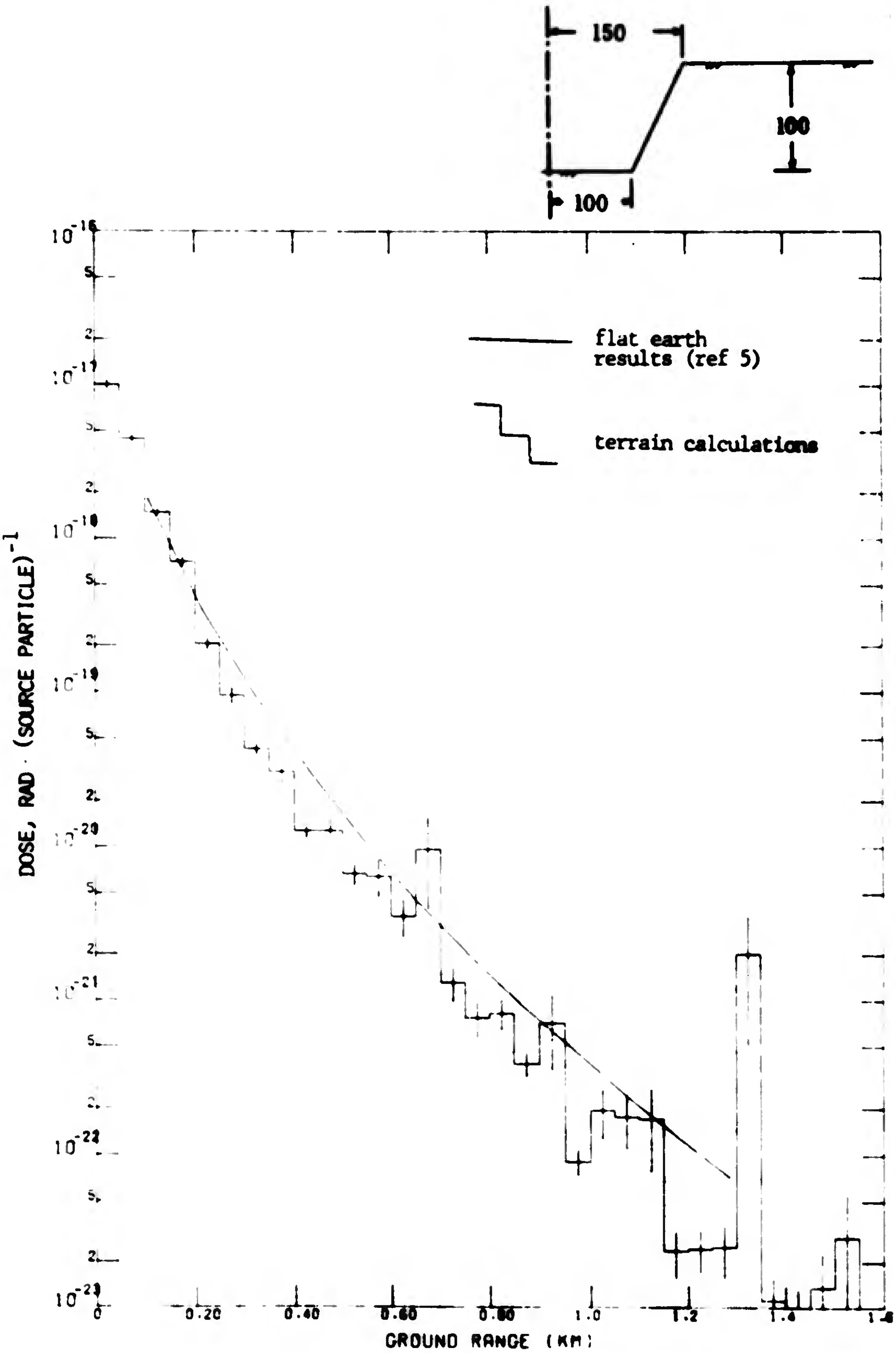


Figure 37. Prompt armor shielded tissue dose versus ground range: hill problem 6, 100 m steep rise to plateau, weapon type A.

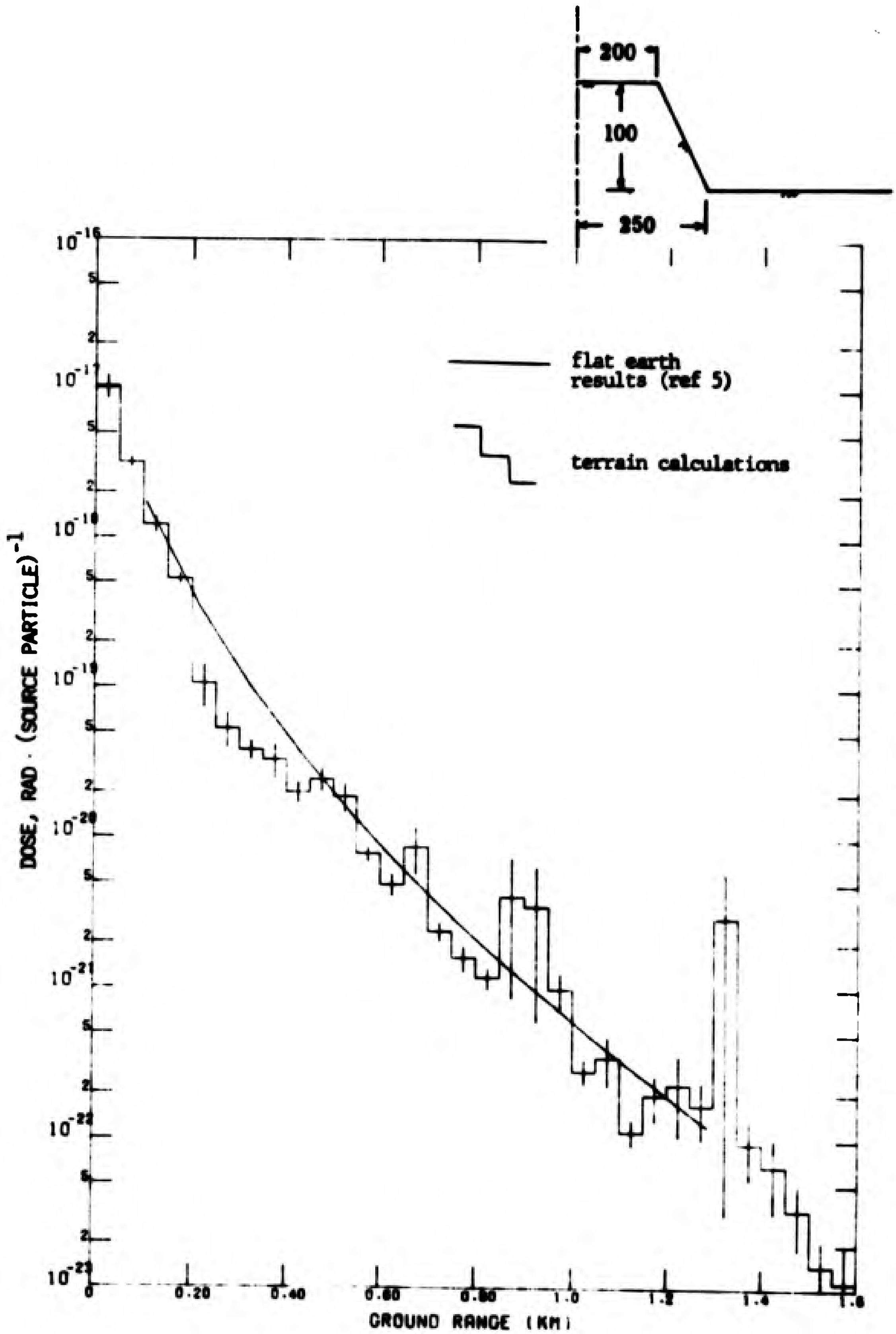


Figure 38. Prompt tissue dose versus ground range: hill problem 7, source above 100 m plateau, weapon type A.

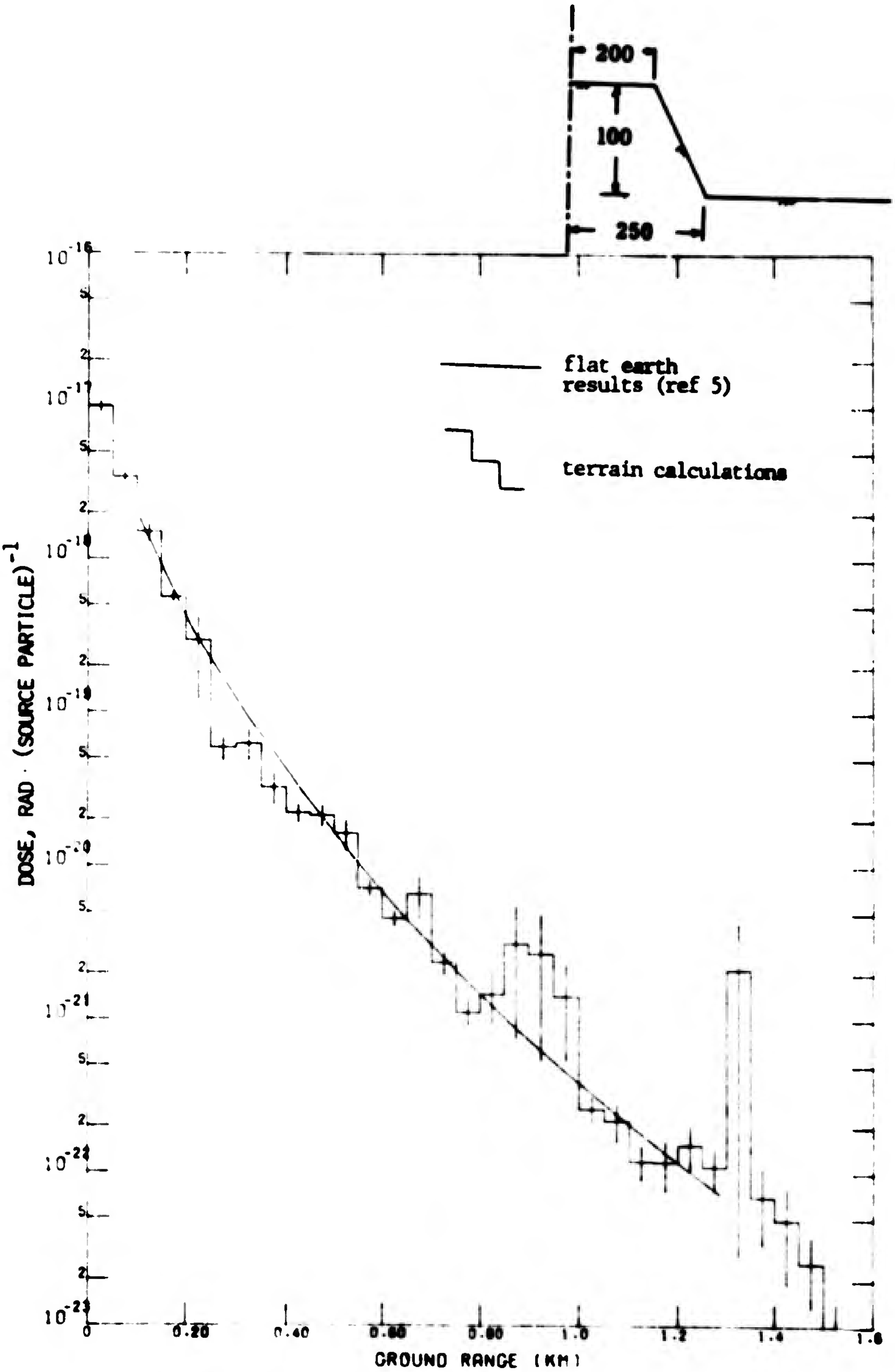


Figure 39. Prompt armor shielded tissue dose versus ground range: hill problem 7, source above 100 m plateau, weapon type A.

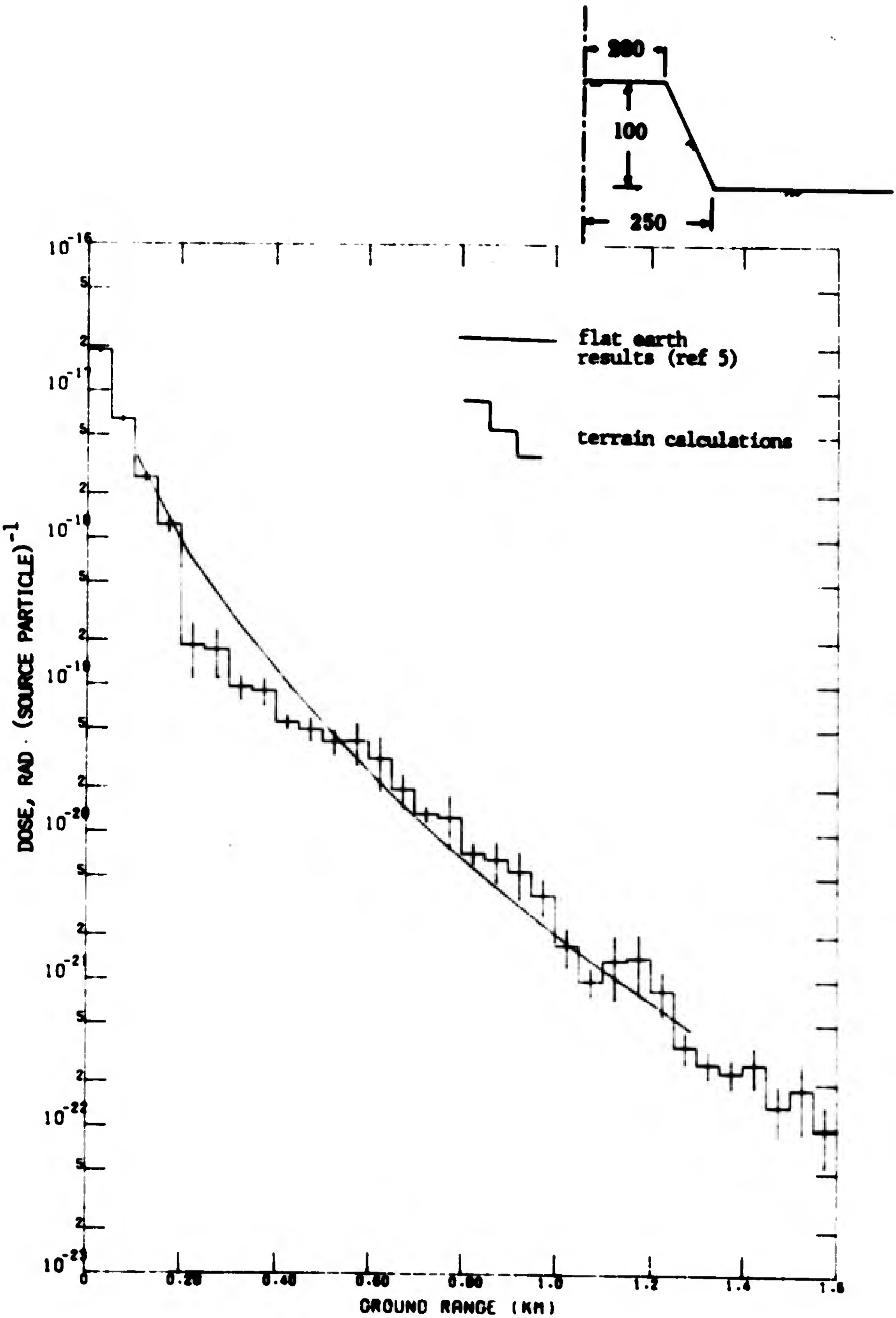


Figure 40. Prompt tissue dose versus ground range: hill problem 8, source above 100 m plateau, weapon type B.

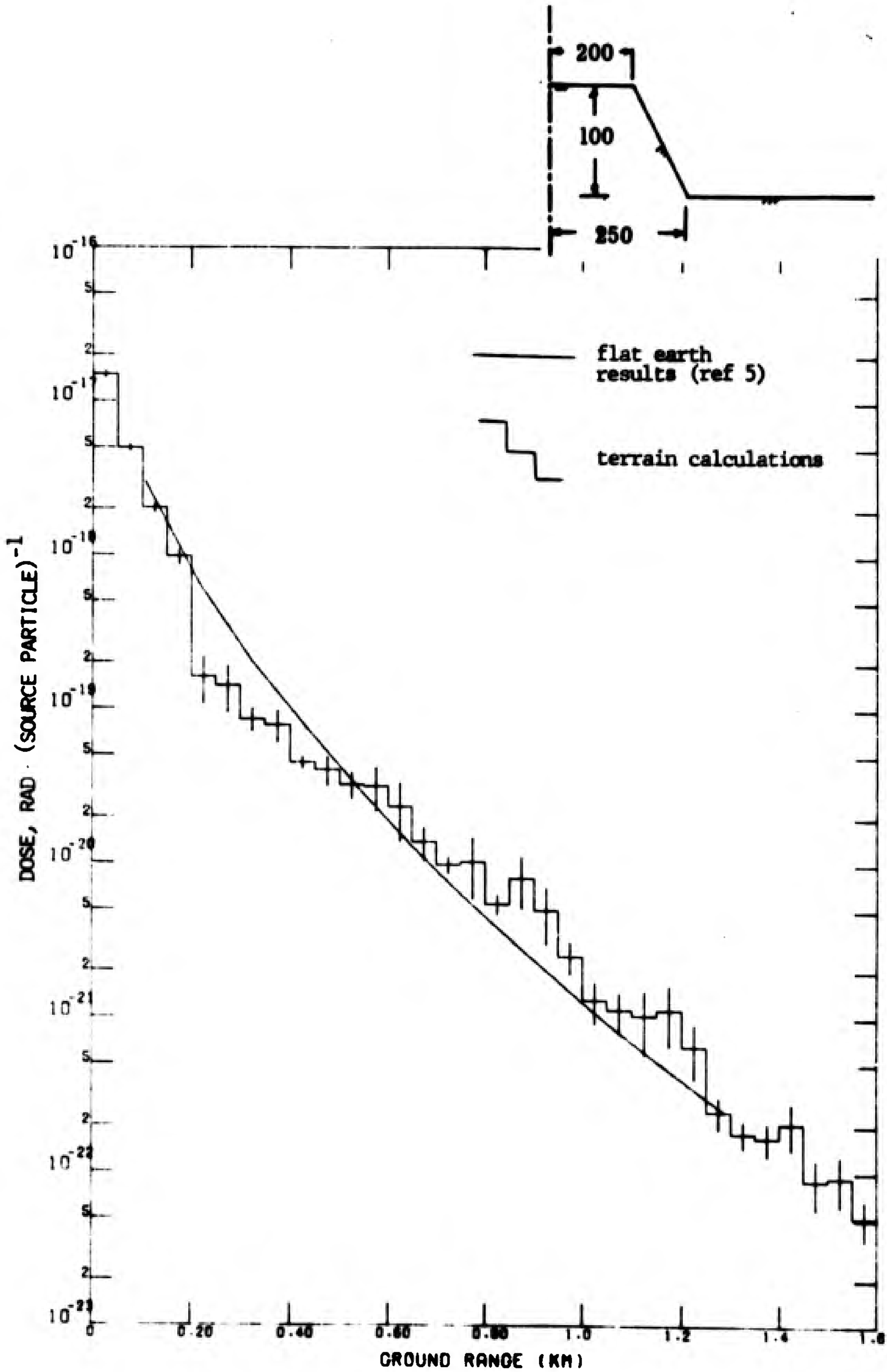


Figure 41. Prompt armor shielded tissue dose versus ground range: hill problem 8, source above 100 m plateau, weapon type B.

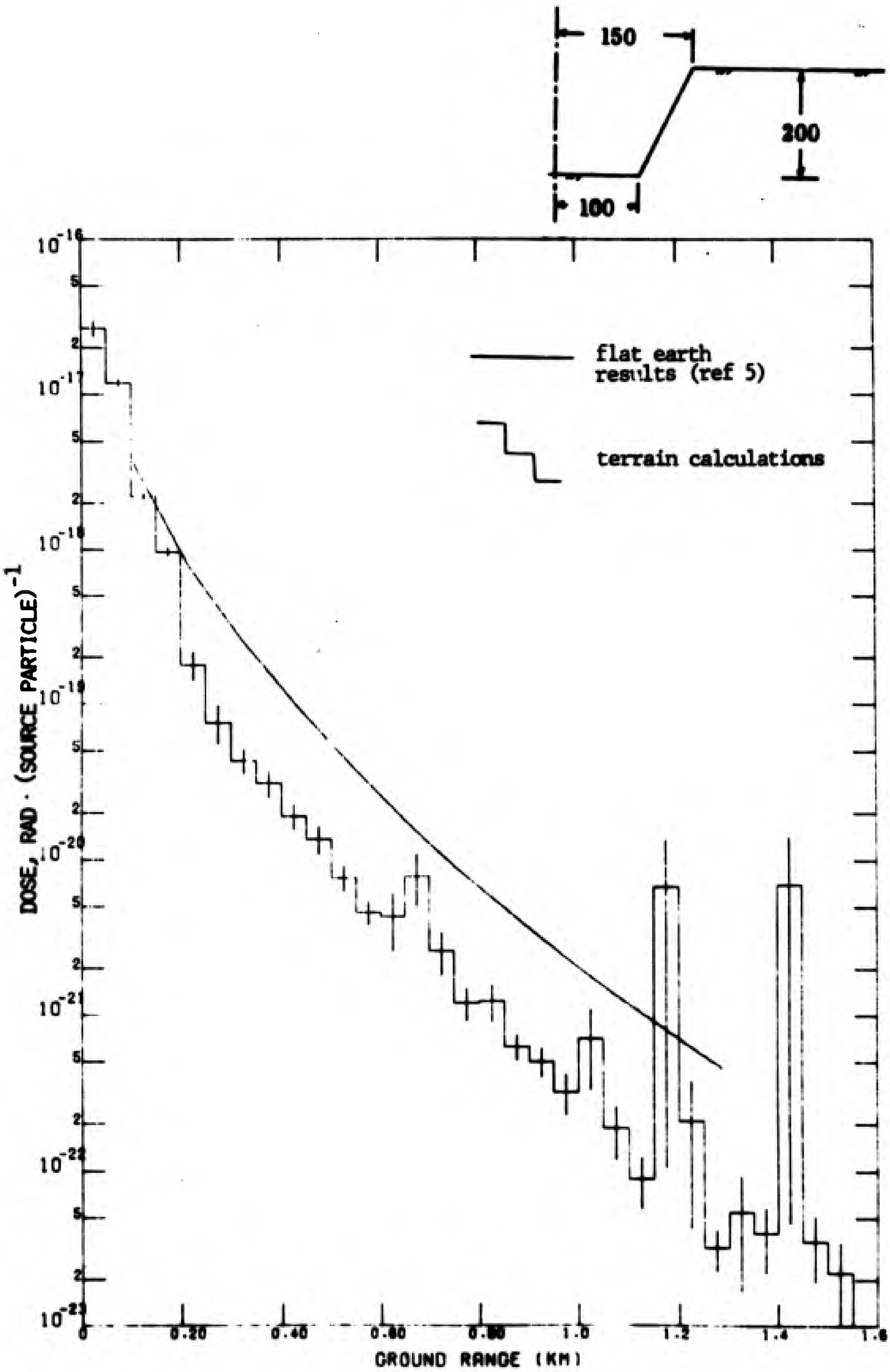


Figure 42. Prompt tissue dose versus ground range: hill problem 9, steep rise to 200 m plateau, weapon type B.

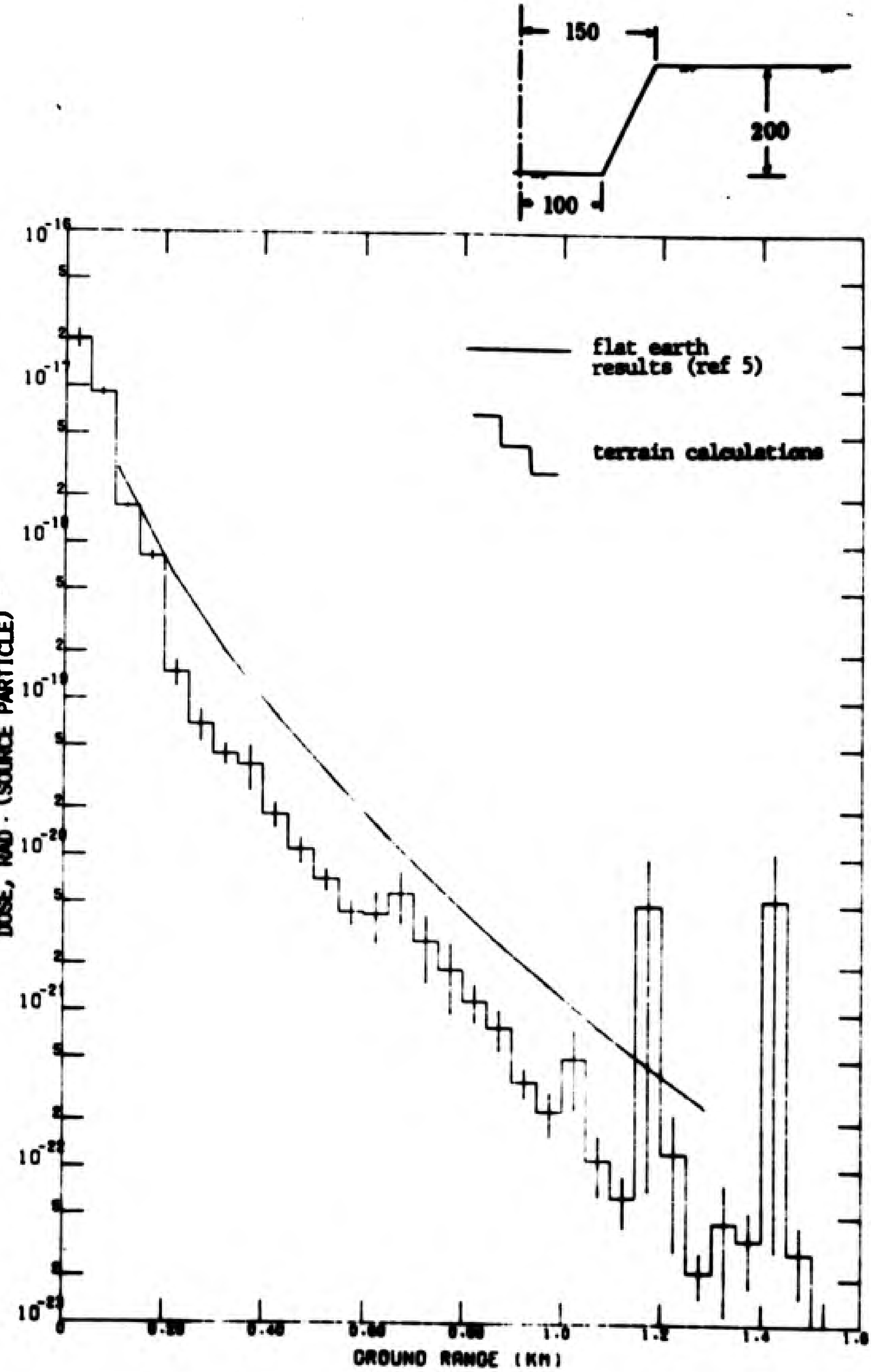


Figure 43. Prompt armor shielded tissue dose versus ground range: hill problem 9, steep rise to 200 m plateau, weapon type B.

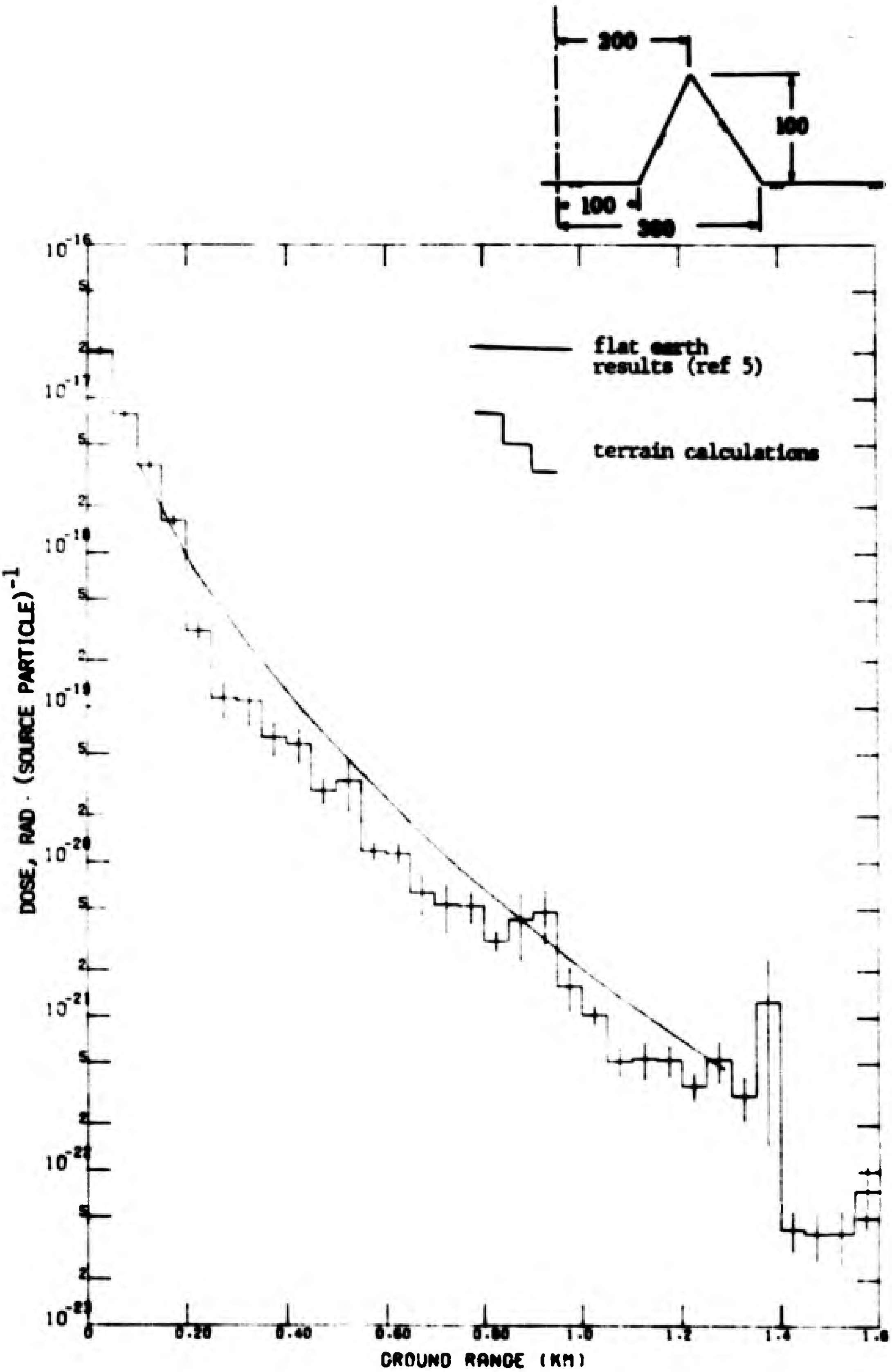


Figure 44. Prompt tissue dose versus ground range: hill problem 10, 100 m hill, weapon type B.

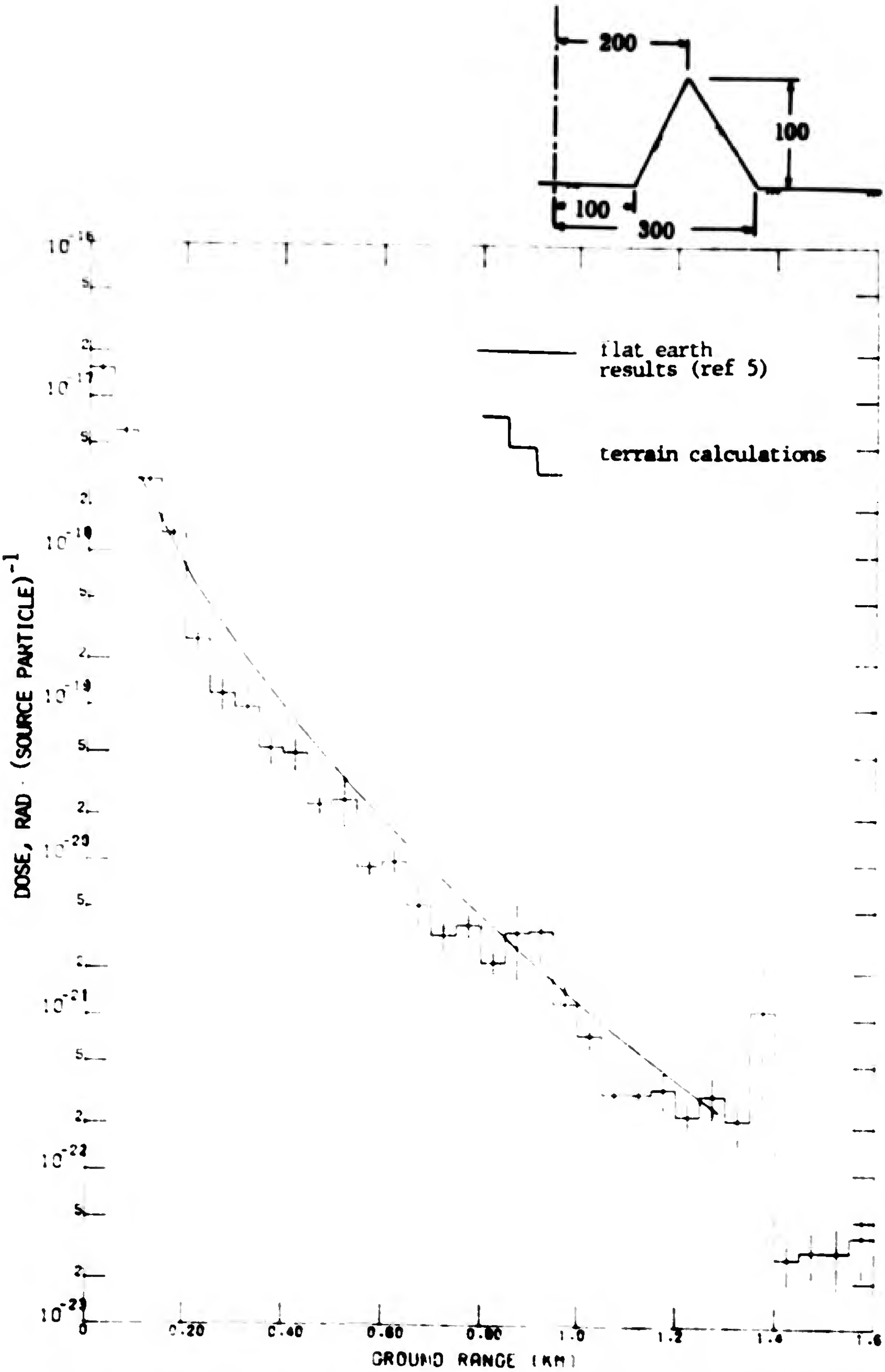


Figure 45. Prompt armor shielded tissue dose versus ground range: hill problem 10, 100 m hill, weapon type B.

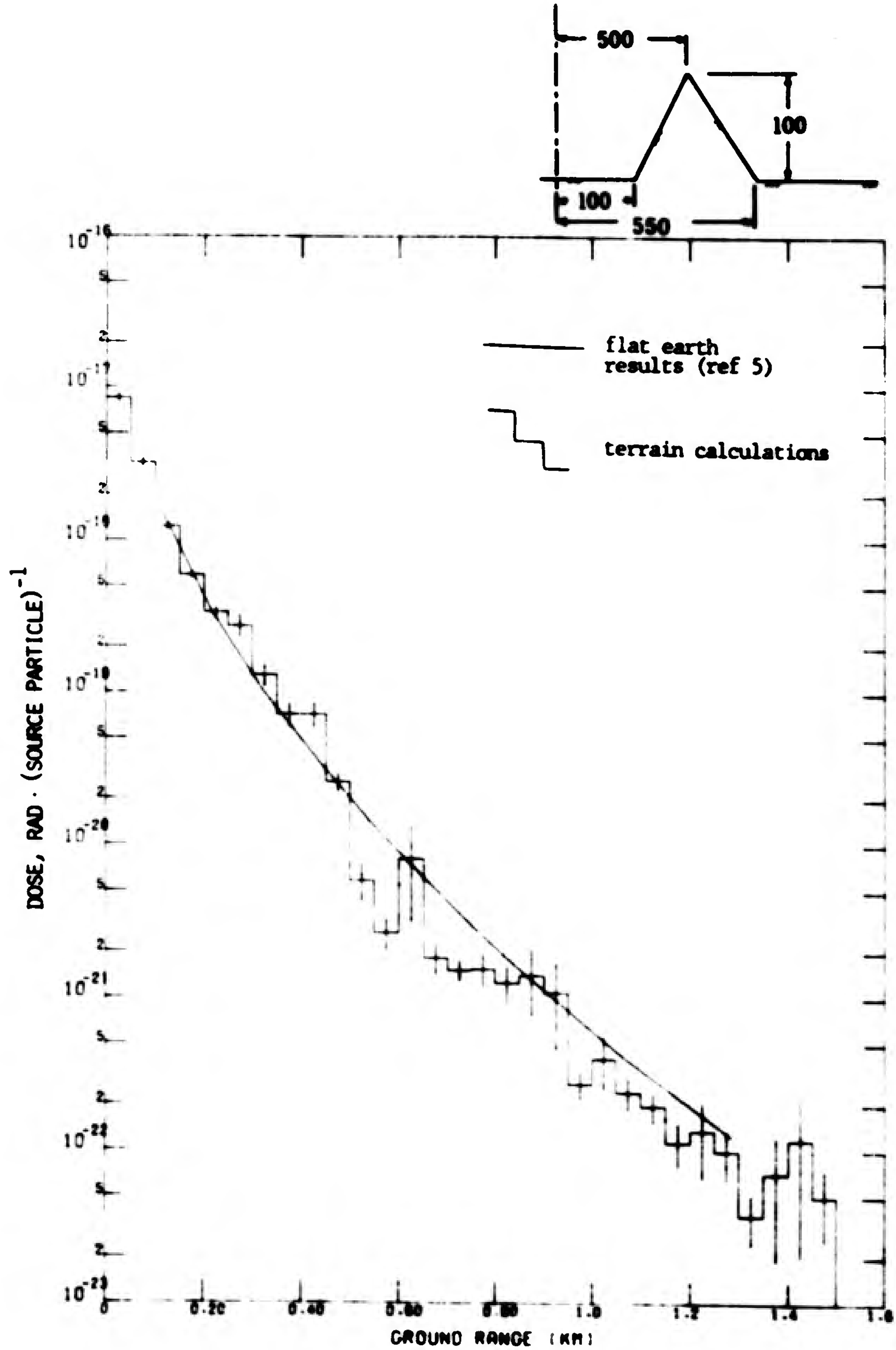


Figure 4 . Prompt tissue dose versus ground range: hill problem 11, 100 m hill at .5 km, weapon type A.

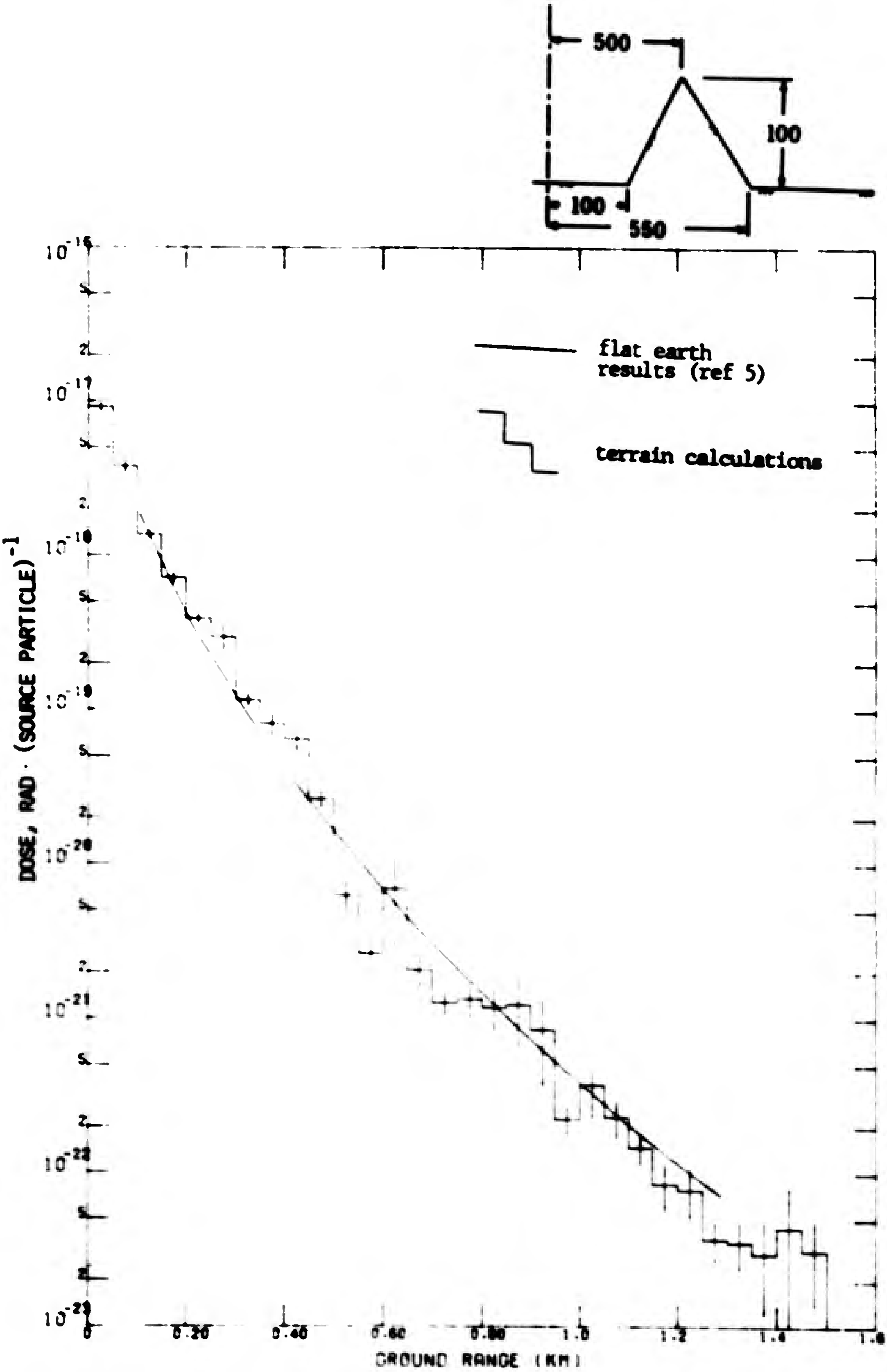


Figure 47. Prompt armor shielded tissue dose versus groung range: hill problem 11, 100 m hill at .5 km, weapon type A.

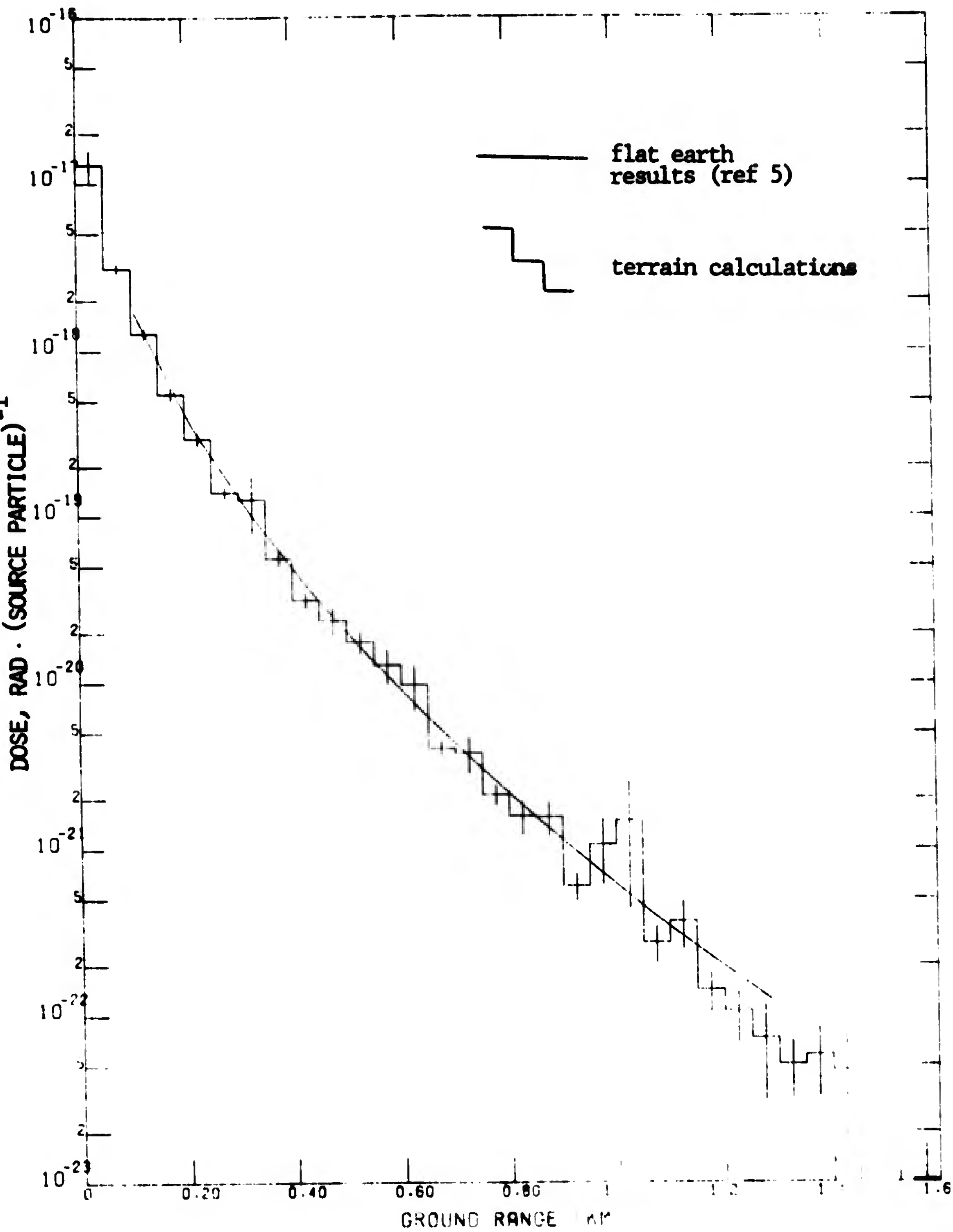


Figure 48. Prompt tissue dose averaged over annular areas for the real terrain problem centered at coordinates (40, 17).

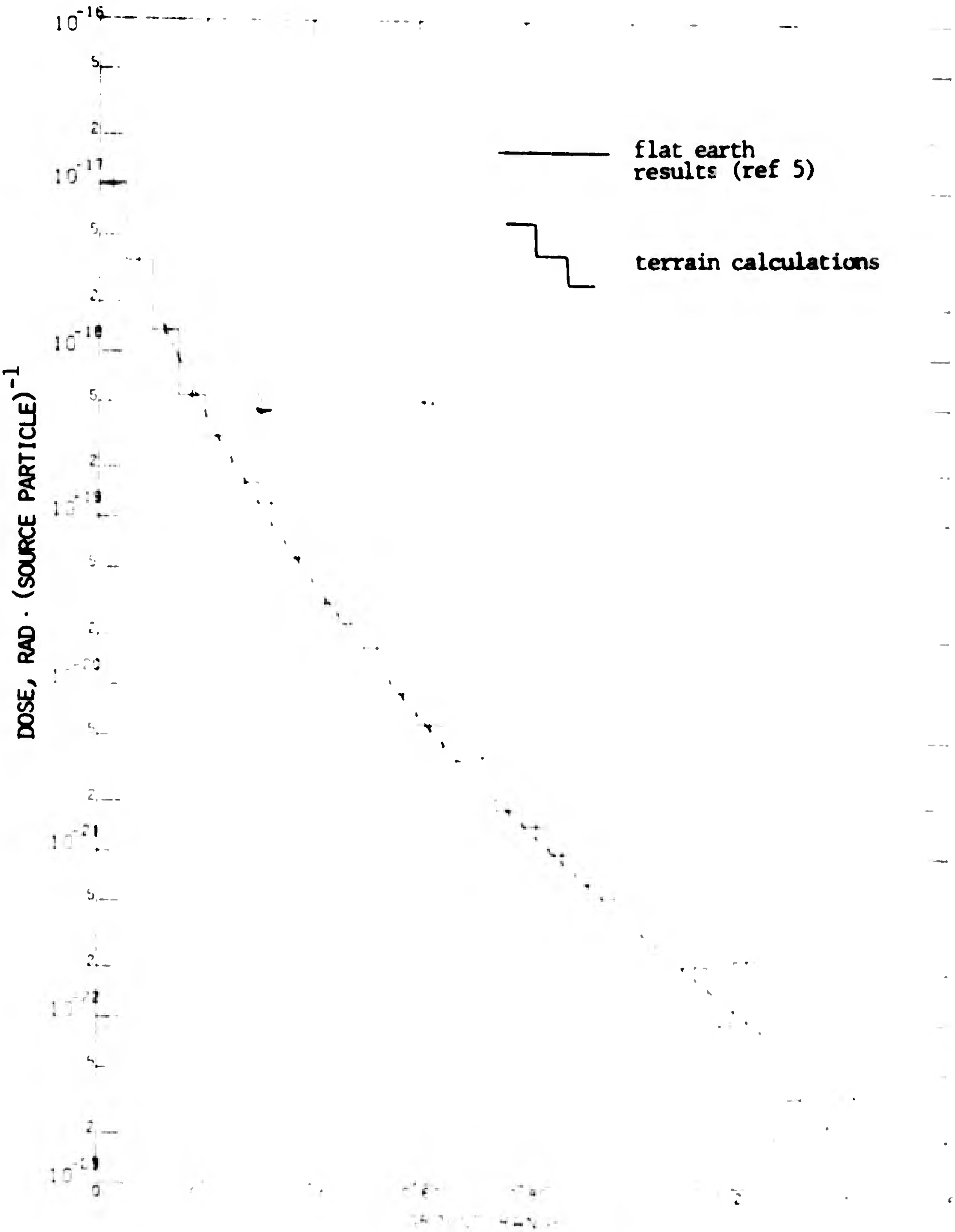


Figure 49. Prompt armor shielded tissue dose averaged over annular areas for the real terrain problem centered at coordinates (40, 17).

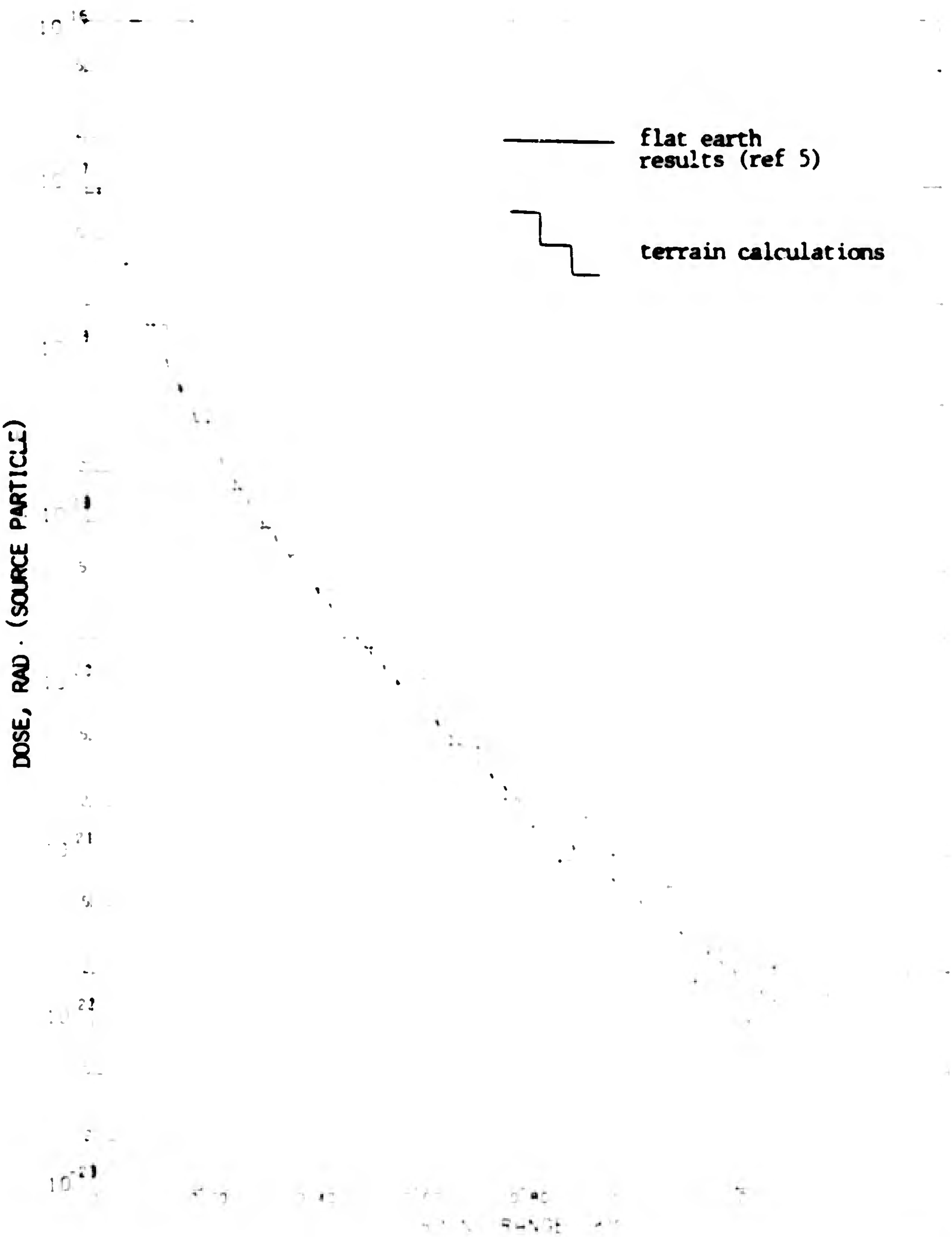


Figure 50. Prompt tissue dose averaged over annular areas for the real terrain problem centered at coordinates (41, 15).

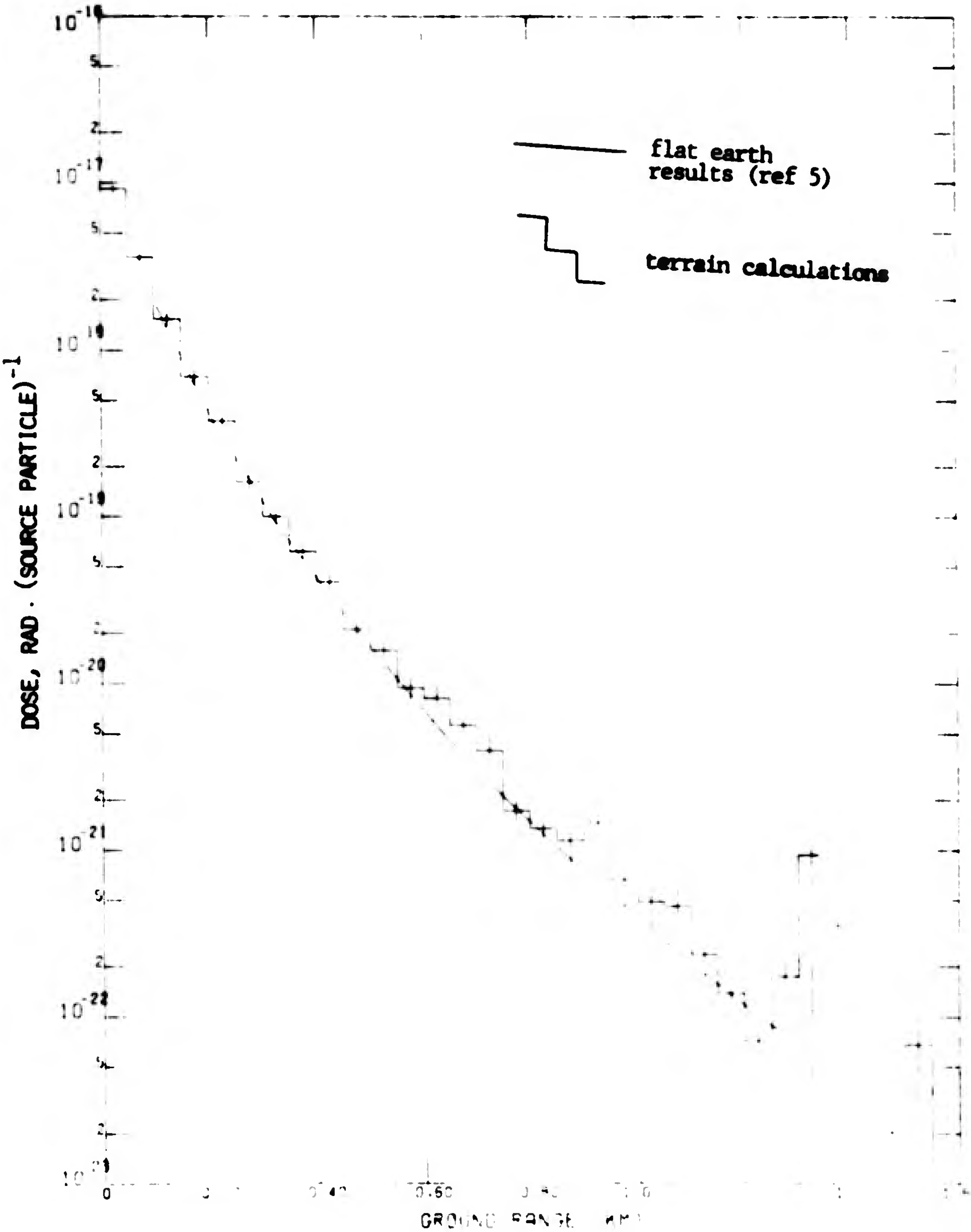


Figure 51. Prompt armor shielded tissue dose averaged over annular areas for the real terrain problem centered at coordinates (41, 15).

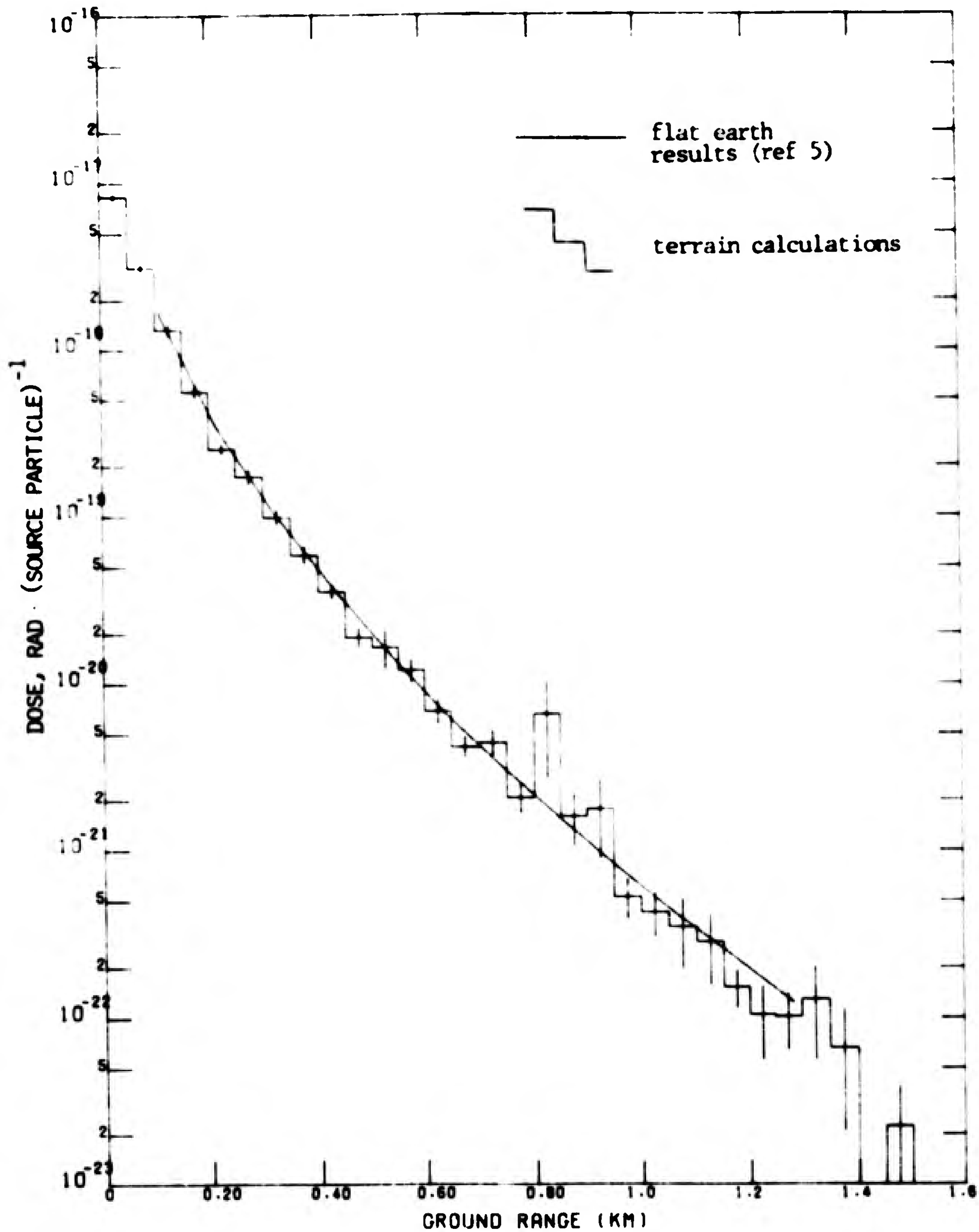


Figure 52. Prompt tissue dose averaged over annular areas for the real terrain problem centered at coordinates (41, 12.4).

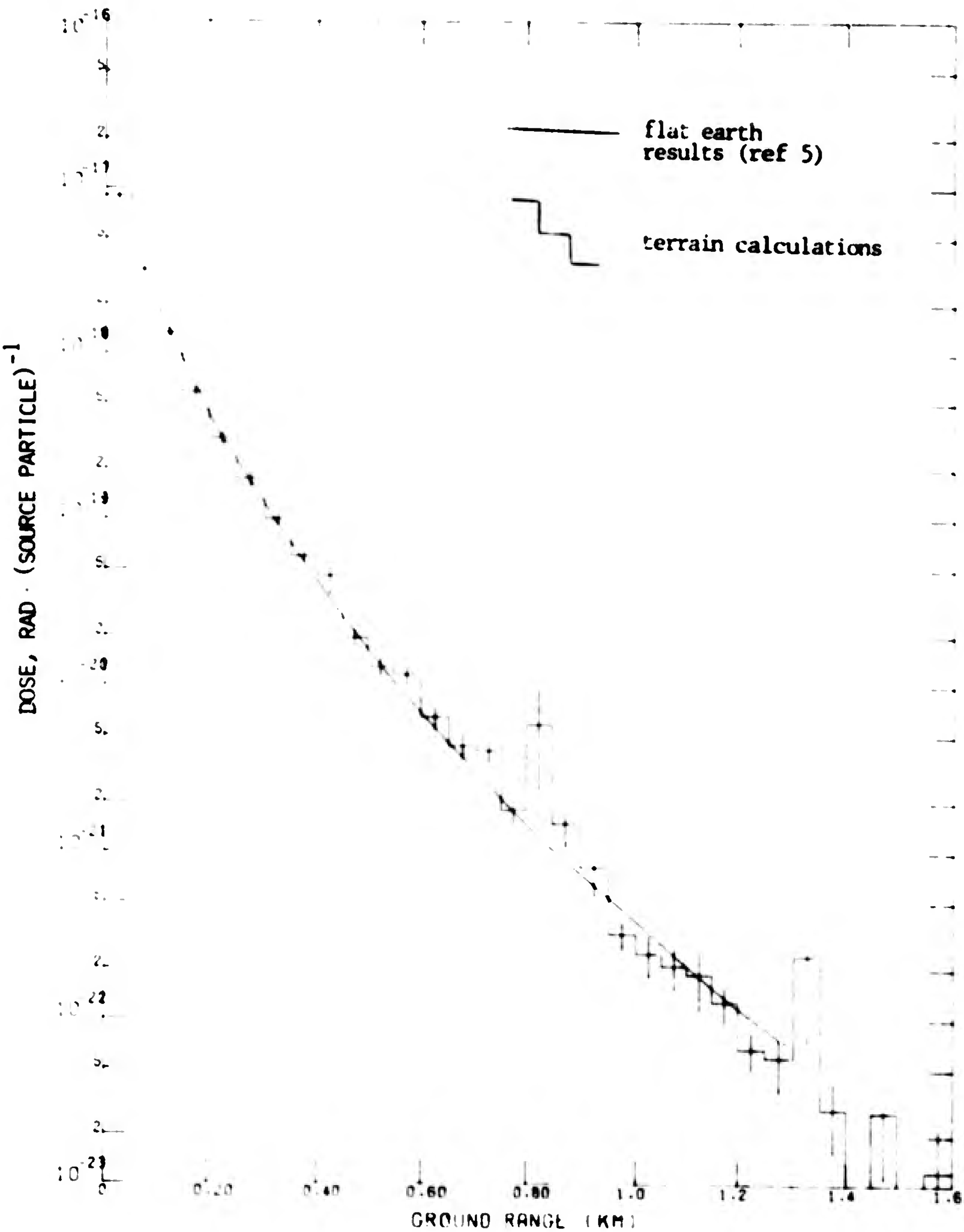


Figure 53. Prompt armor shielded tissue dose averaged over annular areas for the real terrain problem centered at coordinates (41, 12.4).

Table XI. Tabulation of free field tissue dose results for the real terrain problem centered around coordinate (46, 17).

NORTH-SOUTH DISTANCE (METERS)	EAST-WEST DISTANCE (METERS) -900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	1.2E-22	9.4E-23	9.9E-23	5.9E-22	4.9E-22	1.4E-22	4.9E-22	1.9E-22	3.7E-22	2.1E-24	2.
700- 900	2.0E-22	2.0E-22	8.5E-22	4.9E-22	5.8E-22	1.3E-21	1.1E-21	5.0E-22	8.1E-23	1.9E-22	1.3E-23
500- 700	4.7E-23	9.3E-22	7.7E-22	3.0E-21	3.6E-20	6.7E-21	7.5E-21	4.2E-21	5.8E-22	8.8E-23	5.9E-23
300- 500	3.3E-21	1.0E-21	2.1E-21	1.8E-20	2.5E-20	3.9E-20	2.6E-20	2.6E-20	8.2E-21	1.5E-21	2.0E-22
100- 300	7.8E-22	1.1E-21	4.7E-21	3.1E-20	2.3E-19	4.9E-19	2.6E-19	2.9E-20	4.5E-21	1.9E-21	7.9E-22
-100- 100	4.7E-22	4.3E-21	9.6E-21	4.3E-20	4.8E-19	4.7E-18	5.7E-19	3.3E-20	7.2E-21	1.6E-21	2.0E-22
-100- -300	7.5E-22	1.0E-21	7.3E-21	3.0E-22	1.7E-19	4.0E-19	1.4E-19	3.1E-23	5.9E-21	1.9E-21	2.4E-21
-300- -500	5.5E-22	9.5E-22	4.5E-21	8.3E-21	3.2E-22	3.4E-22	4.1E-22	[illegible]	3.8E-21	3.9E-22	9.8E-21
-500- -700	7.9E-23	1.9E-21	1.4E-21	2.4E-21	1.6E-22	7.1E-21	5.6E-21	2.9E-21	[illegible]	5.6E-23	2.5E-22
-700- -900	9.2E-23	2.1E-22	6.4E-22	1.7E-21	1.3E-21	3.3E-21	2.2E-21	7.2E-22	3.4E-22	5.5E-23	3.7E-24
-900- -1100	2.3E-23	1.1E-22	2.4E-22	1.3E-22	6.4E-22	2.4E-21	5.1E-22	9.5E-23	5.5E-23	1.9E-22	1.1E-24

Table XII. Tabulation of armor shielded [illegible] for the real terrain problem centered around coordinate [illegible]

EAST-WEST DISTANCE (METERS)

NORTH-SOUTH DISTANCE (METERS)	-900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	3.2E-23	6.1E-23	9.1E-23	2.0E-22	3.4E-22	9.7E-23	3.8E-22	1.1E-22	3.8E-22	8.2E-24	0.
700- 900	1.0E-22	1.4E-22	6.7E-22	5.8E-22	6.7E-22	1.3E-21	7.8E-22	5.0E-22	4.7E-23	1.4E-22	1.1E-23
500- 700	1.7E-22	3.9E-22	7.0E-22	2.9E-21	1.9E-20	5.1E-21	5.3E-21	3.0E-21	1.1E-21	6.0E-23	[illegible]
300- 500	9.9E-22	1.3E-21	2.0E-21	9.2E-21	2.4E-20	4.4E-20	2.5E-20	2.4E-20	9.4E-21	1.1E-21	[illegible]
100- 300	4.9E-22	1.2E-21	4.1E-21	2.5E-20	2.0E-19	4.9E-19	2.0E-19	2.0E-20	3.0E-21	1.0E-21	3.0E-22
-100- 100	4.1E-22	6.5E-21	9.0E-21	4.7E-20	5.1E-19	4.4E-19	9.8E-19	3.3E-20	7.5E-21	1.3E-21	2.3E-22
-100- -300	4.9E-22	1.4E-21	1.3E-20	3.0E-20	1.9E-19	5.1E-19	1.8E-19	3.0E-20	4.5E-21	1.0E-21	5.1E-22
-300- -500	1.9E-22	7.2E-22	3.0E-21	8.0E-21	3.1E-20	3.0E-20	3.8E-20	9.3E-21	3.9E-21	6.2E-22	3.1E-21
-500- -700	7.2E-23	5.7E-22	7.4E-22	2.2E-21	8.2E-21	7.0E-21	5.4E-21	2.0E-21	6.1E-22	3.9E-23	7.2E-22
-700- -900	1.0E-22	7.0E-23	4.3E-22	1.1E-21	7.9E-22	2.9E-21	1.6E-21	9.1E-22	4.4E-22	6.9E-23	0.
-900- -1100	2.2E-23	1.2E-23	1.9E-21	1.1E-22	4.8E-22	1.1E-21	1.1E-21	1.2E-22	3.8E-23	1.2E-22	1.0E-24

Table XIII. Tabulation of free field tissue dose results for the real terrain problem centered around coordinate (41, 15).

NORTH-SOUTH DISTANCE (METERS)	EAST-WEST DISTANCE (METERS) -900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	2.7E-24	8.4E-23	1.3E-22	3.0E-22	5.2E-22	9.2E-22	1.0E-22	1.0E-21	2.7E-23	3.4E-23	8.9E-24
700- 900	4.4E-22	4.2E-22	6.7E-22	1.0E-21	1.7E-21	2.2E-21	1.7E-21	1.0E-21	2.0E-2[illegible]	2.0E-22	3.[illegible]E-23
500- 700	8.9E-22	3.1E-22	9.0E-22	8.1E-21	8.3E-21	9.4E-21	9.1E-21	4.7E-21	1.4E-21	1.5E-21	[illegible]-22
300- 500	3.1E-22	1.4E-21	2.4E-21	1.3E-20	3.0E-20	4.0E-20	2.4E-20	1.0E-20	2.7E-21	1.9E-21	4.0E-23
100- 300	1.0E-22	5.0E-21	8.5E-21	2.7E-20	1.0E-19	7.1E-19	1.0E-19	4.1E-20	5.0E-21	1.1E-21	5.0E-22
-100- 100	1.0E-21	3.9E-21	4.0E-21	4.3E-20	7.2E-19	4.1E-18	4.9E-19	5.0E-20	9.0E-21	1.1E-21	2.0E-21
-100- -300	5.6E-22	2.0E-21	3.0E-20	2.9E-20	2.9E-19	6.2E-19	1.0E-19	3.5E-20	4.9E-21	6.9E-22	2.7E-22
-300- -500	1.1E-22	3.7E-22	3.9E-21	1.9E-20	2.2E-20	6.0E-20	4.9E-20	1.0E-20	2.9E-21	3.7E-22	4.9E-23
-500- -700	8.1E-23	1.1E-21	8.5E-22	3.4E-21	6.3E-21	9.0E-21	6.0E-21	2.0E-21	1.1E-21	3.0E-22	6.4E-23
-700- -900	2.4E-22	1.0E-22	4.2E-22	1.1E-21	1.9E-21	1.9E-21	7.0E-22	4.0E-22	1.2E-21	4.1E-23	7.7E-23
-900- -1100	6.9E-24	3.7E-22	9.4E-22	3.9E-22	1.5E-22	4.7E-21	1.1E-21	7.0E-22	7.7E-23	3.2E-24	2.9E-22

Table CIV. [illegible] problem centered [illegible]

EAST-WEST DISTANCE (METERS)

NORTH-SOUTH DISTANCE (METERS)	-900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	1.1E-23	2.7E-23	1.0E-22	3.9E-23	7.9E-23	2.0E-22	2.9E-22	1.9E-22	2.7E-23	7.3E-23	0.
700- 900	1.3E-22	4.2E-22	3.5E-22	1.1E-21	1.7E-21	1.3E-21	8.4E-22	2.3E-20	6.2E-22	4.2E-23	1.0E-23
500- 700	2.0E-22	8.0E-22	9.7E-22	2.1E-21	5.5E-21	1.1E-20	6.9E-21	5.0E-21	1.4E-21	1.5E-22	2.9E-23
300- 500	2.3E-22	7.0E-22	1.4E-21	1.2E-20	3.4E-20	5.7E-20	2.9E-20	1.7E-20	5.4E-21	1.3E-21	2.1E-22
100- 300	4.4E-22	5.9E-21	9.5E-21	3.1E-20	1.9E-19	5.2E-1[illegible]	1.7E-19	7.2E-20	4.7E-21	3.7E-21	3.3E-22
-100- 100	2.0E-22	8.5E-22	9.0E-21	4.0E-20	5.9E-19	4.2E-19	4.9E-19	4.7E-20	8.5E-21	2.4E-21	3.2E-22
-100- -300	9.5E-23	6.2E-21	6.1E-21	2.2E-20	2.7E-19	5.6E-19	1.5E-19	2.3E-20	4.0E-21	3.4E-21	3.0E-22
-300- -500	4.0E-22	6.2E-22	4.3E-21	1.2E-20	[illegible].7E-20	4.7E-20	3.4E-20	1.1E-20	1.9E-21	6.0E-22	1.3E-22
-500- -700	1.2E-22	2.5E-22	4.4E-22	3.0E-21	6.5E-21	7.0E-21	8.9E-21	3.1E-21	7.6E-22	2.9E-22	1.4E-22
-700- -900	2.9E-23	8.4E-23	3.9E-22	8.0E-22	4.0E-21	3.1E-21	9.7E-22	5.1E-22	1.0E-22	1.0E-22	2.2E-23
-900- -1100	7.6E-23	1.0E-21	4.7E-23	6.0E-22	3.9E-22	5.3E-22	6.6E-22	1.0E-22	3.5E-20	1.7E-22	9.0E-24

Table XV. Tabulation of free field tissue dose results for the real terrain problem centered around coordinates [illegible].

EAST-WEST DISTANCE (METERS)

NORTH-SOUTH DISTANCE (METERS)	-900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	1.1E-23	4.1E-23	5.9E-23	4.0E-22	4.9E-22	3.2E-22	1.8E-22	5.1E-22	1.7E-23	2.5E-23	6.0E-24
700- 900	9.9E-21	4.0E-22	5.7E-22	8.0E-22	1.9E-21	2.2E-21	2.8E-21	1.1E-21	1.9E-21	2.7E-22	2.7E-23
500- 700	6.9E-22	2.0E-22	6.0E-22	4.9E-21	7.1E-21	6.2E-21	8.7E-21	3.1E-21	1.2E-21	1.3E-21	4.4E-22
300- 500	2.3E-22	1.4E-21	2.1E-21	1.2E-20	3.7E-20	5.0E-20	2.7E-20	2.3E-20	2.4E-21	1.5E-21	6.3E-23
100- 300	2.0E-22	4.7E-21	1.1E-20	4.7E-20	1.7E-19	6.4E-19	1.8E-19	4.3E-20	5.9E-21	1.2E-21	8.8E-22
-100- 100	7.0E-22	2.4E-21	9.8E-21	4.6E-20	7.9E-19	4.2E-18	5.5E-19	5.1E-20	1.2E-20	1.7E-21	1.2E-21
-100- -300	3.8E-22	2.1E-21	1.7E-20	2.5E-20	1.8E-19	6.2E-19	1.8E-19	3.6E-20	4.7E-21	6.3E-22	1.3E-22
-300- -500	5.6E-23	3.2E-22	3.1E-21	2.1E-20	2.1E-20	5.4E-20	4.3E-20	9.2E-21	2.4E-21	5.3E-22	3.1E-23
-500- -700	6.3E-23	3.3E-21	8.3E-22	3.0E-21	4.8E-21	7.5E-21	8.4E-21	2.8E-21	5.8E-22	1.6E-22	6.3E-23
-700- -900	2.1E-22	1.3E-22	2.4E-22	1.0E-21	1.8E-21	1.3E-21	7.7E-22	4.5E-22	8.7E-22	2.4E-23	6.8E-23
-900- -1100	4.9E-24	2.0E-22	1.2E-22	3.9E-22	1.3E-22	1.7E-21	7.8E-22	6.2E-22	9.4E-23	1.4E-24	7.3E-22

EAST-WEST DISTANCE (METERS)

NORTH-SOUTH DISTANCE (METERS)	-900 -1100	-700 -900	-500 -700	-300 -500	-100 -300	-100 100	100 300	300 500	500 700	700 900	900 1100
900- 1100	8.1E-24	8.4E-24	2.1E-22	4.2E-23	8.4E-23	2.1E-22	5.7E-22	2.8E-22	7.8E-24	9.0E-23	9.2E-24
700- 900	9.9E-23	3.1E-22	8.9E-22	1.2E-21	8.7E-22	1.8E-21	8.1E-22	2.5E-20	8.1E-22	7.0E-23	4.0E-23
500- 700	9.9E-22	7.8E-22	1.2E-21	[illegible]	8.2E-21	1.3E-20	5.8E-21	7.2E-21	1.8E-21	1.5E-22	3.4E-23
300- 500	3.3E-22	9.8E-22	1.7E-21	[illegible]	5.8E-20	5.2E-20	2.8E-20	1.8E-20	5.2E-21	5.2E-21	1.9E-22
100- 300	1.1E-21	9.9E-21	9.4E-21	[illegible]	[illegible]	[illegible]	[illegible]	4.1E-20	5.5E-21	4.1E-21	7.3E-22
-100- 100	3.3E-22	1.3E-21	7.8E-21	[illegible]	[illegible]	3.8E-18	4.2E-19	4.5E-20	1.2E-20	3.4E-21	3.3E-22
-100- -300	[illegible]	8.7E-21	8.7E-21	2.1E-20	[illegible]	5.1E-19	1.4E-19	2.2E-20	8.7E-21	4.7E-21	4.0E-22
-300- -500	1.4E-21	[illegible]	4.3E-21	1.4E-20	[illegible]	4.3E-20	5.8E-20	9.3E-21	[illegible]	8.8E-22	1.0E-22
-500- -700	2.3E-22	3.7E-22	8.2E-22	[illegible]	[illegible]	8.2E-21	8.2E-21	2.2E-21	8.7E-22	1.7E-22	1.0E-22
-700- -900	1.2E-22	-9.3E-23	1.2E-21	1.1E-21	3.8E-21	1.8E-21	1.1E-21	8.5E-22	1.9E-22	2.8E-22	3.0E-23
-900- -1100	2.9E-22	3.7E-22	9.7E-23	1.2E-21	4.7E-22	8.4E-22	1.7E-21	4.1E-22	1.1E-24	2.1E-22	1.2E-23

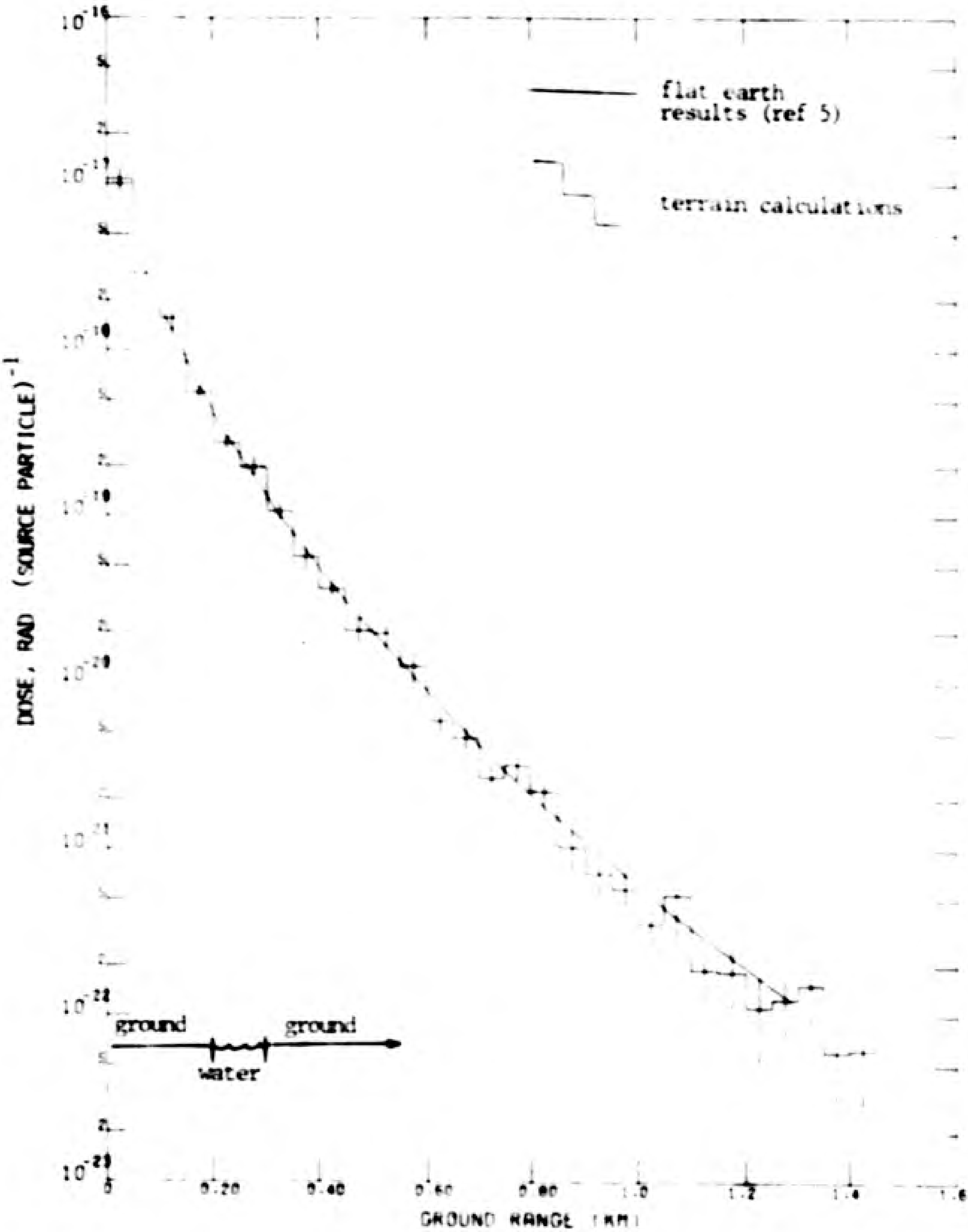


Figure 54. Tissue dose versus ground range with 100 meter water annulus.

5. ANALYSIS AND DISCUSSION OF RESULTS

5.1 The Effects of a Dense Forest Cover

From an examination of Figures 12 through 22, several observations can be made:

1) for distances greater than about 300 meters from ground zero the dose ratio is relatively constant,
2) there is a 10 to 15% variation about a mean value in the dose ratio depending on weapon type, and
3) the maximum protection factor provided by a dense forest is approximately a factor of 3 for surface bursts and decreases slowly with burst height

Oscillations in the dose ratio seen at the higher source heights are due to residual ray effects in the transport calculations and should not be confused with the effects of the forest layer which would be a smooth line through the oscillations.

The first observation differs strongly with the earlier estimates of the transmission of neutrons and gamma rays through forests presented in Table I The exponential behavior of the previous estimates indicate that only attenuation along the line of sight between the burst and detector was considered The results of the present calculations indicate that attenuation along the line of sight is not the predominant factor. Rather, it appears that the forest provides a rather constant attenuation of the direct and scattered nuclear radiation impinging on the forest canopy in the near vicinity of the detector In radiation transport terminology, it appears that the major effect is an attenuation of the adjoint flux with the forward flux incident on the forest canopy being little affected by the presence of the forest. The effect of the forest is most important around the detector with the effect on the source being only a slight decrease in the effective burst height.

Except for small ground ranges (where other effects such as forest blowdown would predominate prompt personnel dose effects), the effects of a dense forest can be represented by a constant which is independent of ground range and only slightly dependent on weapon type and source height.

The conclusion from the sensitivity calculations shown in Table X is that the effects of forest cover are controlled by the neutron cross section for hydrogen. The sensitivity function calculated for hydrogen is negative for neutron energies above 1 keV and is a maximum (absolute value) in the 100 to 500 keV energy range. A negative sensitivity indicates that the effect of interest (tissue dose) would be expected to decrease due to increases in the macroscopic hydrogen cross section in this energy range. Uncertainties in the macroscopic cross section can be due either to uncertainties in the material composition or to uncertainties in microscopic cross section data. For neutron energies below 1 keV, the positive sensitivity is due to the production of secondary gamma rays. The sensitivity function for the macroscopic hydrogen cross section indicates that the dominant mechanism involved in this problem is the elastic scattering of neutrons with hydrogen nuclei resulting in a degradation of neutron energy and a consequently lower tissue dose.

5.2 The Effects of Topography

The first two figures (16 and 17) for flat terrain are shown in order to demonstrate the absence of any systematic errors or differences between the present calculations and those reported in the calculations by Gritzner et. al.[5]. As mentioned previously, most of the Monte Carlo calculations reached a 25% fractional standard deviation at a horizontal ground range of 1 kilometer. Better statistics could have been obtained with larger sample sizes and correspondingly longer computing times. However, an a priori assumption was made that terrain effects smaller than 25% would not be considered significant since the inaccuracies of prompt personnel dose calculations in air over ground geometry are on that order[5]. Therefore, higher precision Monte Carlo calculations were not required.

5.2.1 Idealized Topography

5.2.1.1 Valleys

The first valley (crater) calculation shown in Figure 18 was for a valley slope of 15°. No significant terrain effect can be observed for either free field or armor shielded tissue dose. The second valley problem increased the valley slope to 30° where small terrain effect can be observed as shown in Figures 20 and 21.

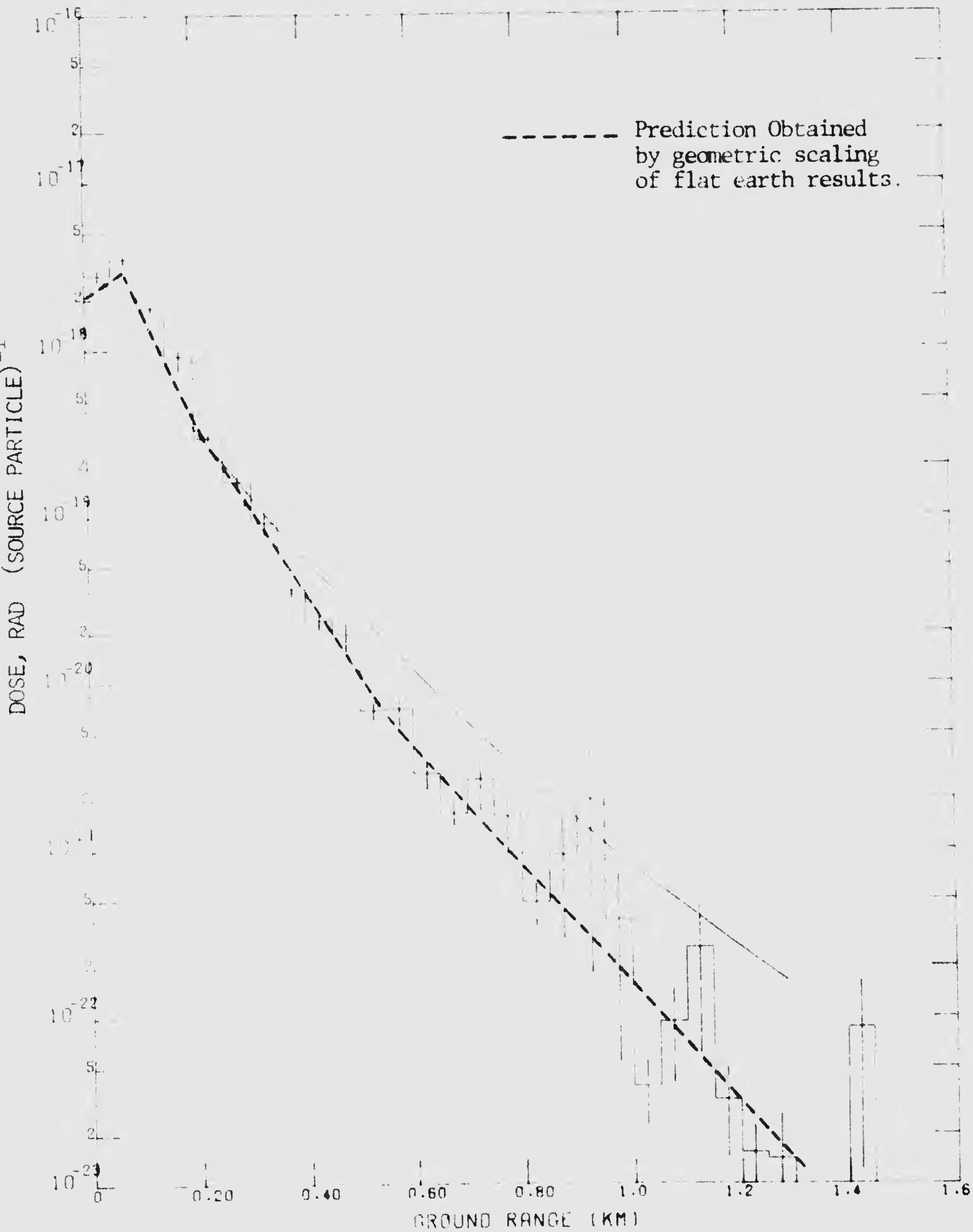


Figure 55. Comparison of valley problem No. 3 with geometrically scaled flat earth results.

Analysis of this calculation showed that the observed terrain effect could be explained by geometrical scaling. That is, the tissue dose plotted as a function of slant range was consistent with flat earth calculations. To test this observation in an extreme case, problem 3 was calculated which had a valley slope of 45^{o} and a burst height of 130 meters. These results are shown in Figures 22 and 23. Figure 55 shows a replot of Figure 22 with the addition of a broken line which gives a prediction of the dose from simple geometric scaling of flat earth results. Simple geometric scaling refers to scaling flat earth results to an equivalent slant range (equivalent areal mass).

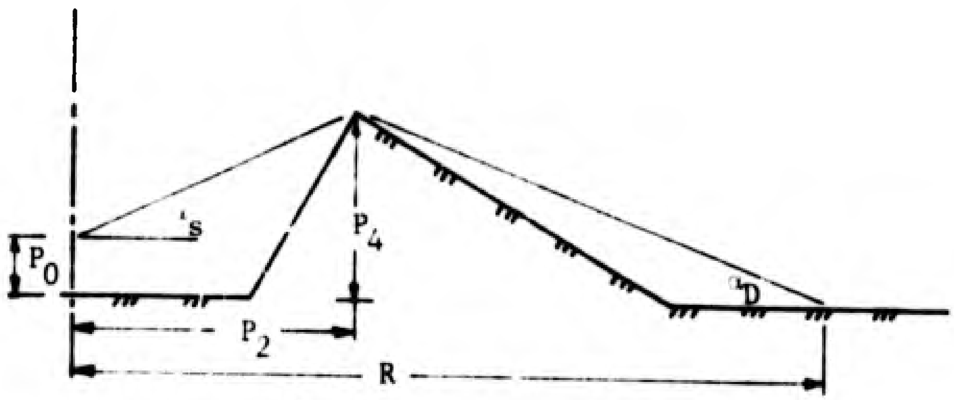
One additional valley calculation was performed to explore the effects of a different weapon spectra. No significantly different effect was observed. No evidence of a statistically significant enhancement effect due to reflection from the valley walls was observed. This was the case even for extremely unrealistic valley slopes. The lack of sensitivity of the cylindrically symmetric valley calculations to reflection from opposing walls supports the approach in this study of calculating cylindrically symmetric hills.

5.2.1.2 Hills

Several general observations can be made about the terrain effects produced by idealized hills by examining the matrix of calculations that were performed. First, where line of sight exists between source and detector, no statistically significant terrain effect can be attributed to the presence of the hill. A second general observation is that for a given problem, the terrain effects for armor shielded dose appear to be slightly smaller than for free field tissue dose.

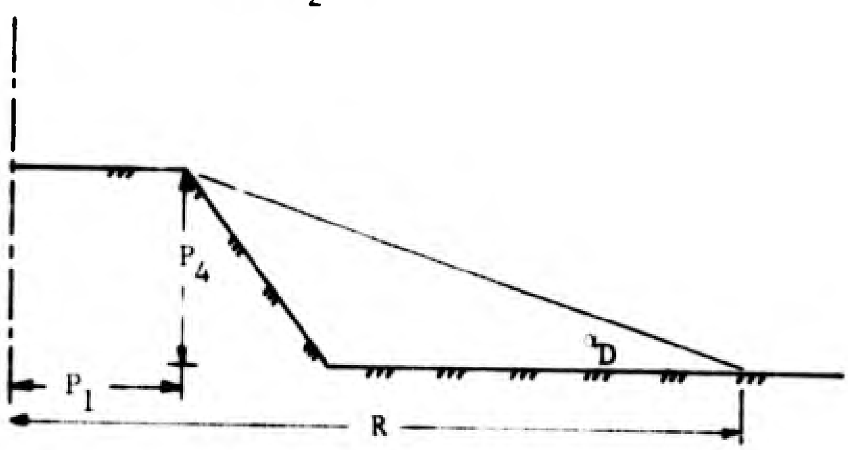
In the shadowed regions of the idealized hill problems, terrain protection factors of up to a factor of 5 can be observed. From this rather sparse matrix of calculations, an attempt has been made to devise a rough parameterization of the results.

For those situations in which the line of sight between the source and detector is obscured by intervening terrain, it is reasonable to expect that the terrain protection factor is a function of the angle the obscuring terrain subtends with respect to the source and detector. These two angles, α_S and α_D are illustrated in Figure 56.



$$\alpha_S = \arctan\left(\frac{P_4 - P_0}{P_2}\right)$$

$$\alpha_D = \arctan\left(\frac{P_4}{R - P_2}\right)$$



$$\alpha_D = \arctan\left(\frac{P_4}{R - P_1}\right)$$

Figure 56. Illustration of subtended angles for obscuring terrain.

The terrain protection factor is defined as the ratio of tissue dose at a given horizontal ground range for a flat earth to the corresponding value for the terrain geometry. When the terrain protection factors are plotted as a function of α_S and α_D, a reasonable pattern of consistency can be observed. This presentation of results is given in Figure 57. The solid lines are an estimate of the "iso-protection factor" contours. The symbols show data points determined from the calculations.

The last hill problem, number 11, was executed as a test of the parameterization. Though not intended to be a conclusive test, the (α_S and α_D) parameterization appears to fit the terrain effects observed in the present calculations. If and when expanded calculations are available, improved parameterizations may be obtained.

At first observation hill problem number 8 exhibits a surprising effect. This problem represents a burst occurring over a plateau region of 200 meter radius with the surrounding terrain 100 meters below the level of ground zero. The geometry is such that the region between approximately 200 meters and 600 meters is obscured from the burst. Beyond 600 meters, line of sight exists. The surprising observation is that the tissue dose beyond 600 meters is slightly larger than the flat earth results. In fact the dose beyond 600 meters agrees suspiciously well with flat earth calculations for a burst height of 140 meters as shown in Figure 58. The indication is that the dose where line of sight exists behaves as if the hill was not present. The analysis of this problem prompted the careful wording of the first general observation that where line of sight exists no statistically significant terrain effect can be attributed to the presence of a hill.

Problem number 7 has the same geometry as problem 8 but with a different weapon source. For this case the results are not explained by an effectively larger burst height. There appears to be subtle source spectra sensitivities that future analysis may uncover.

A summary table of the results of the idealized topographic calculations is given in Table XVII which tabulates the approximate attenuation factor at 1000 meters horizontal ground range for each of the problems. The attenuation factors can be seen to range in value from .75 (an enhancement) to 8.

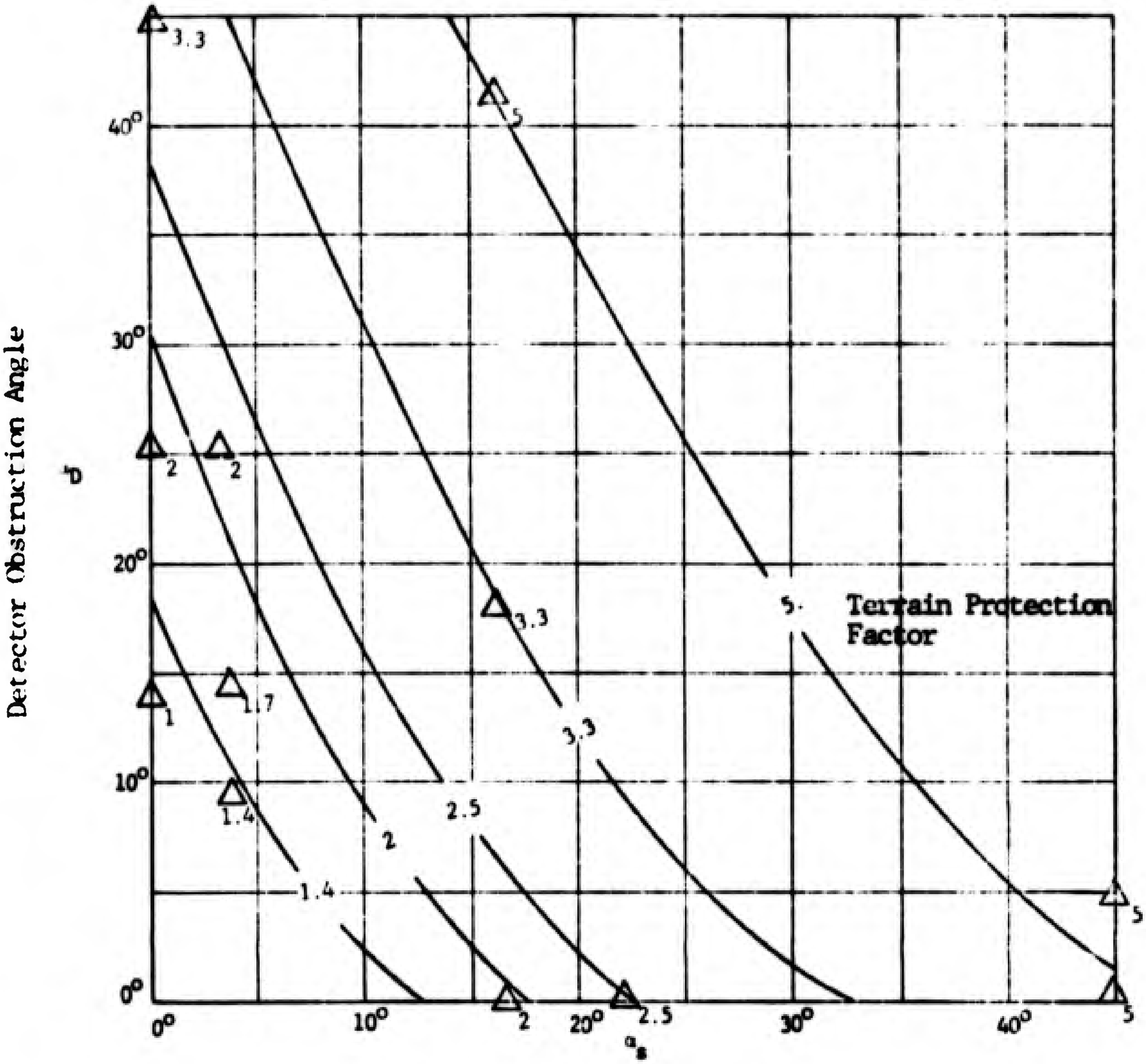


Figure 57. A simple parameterization of the idealized hill calculations.

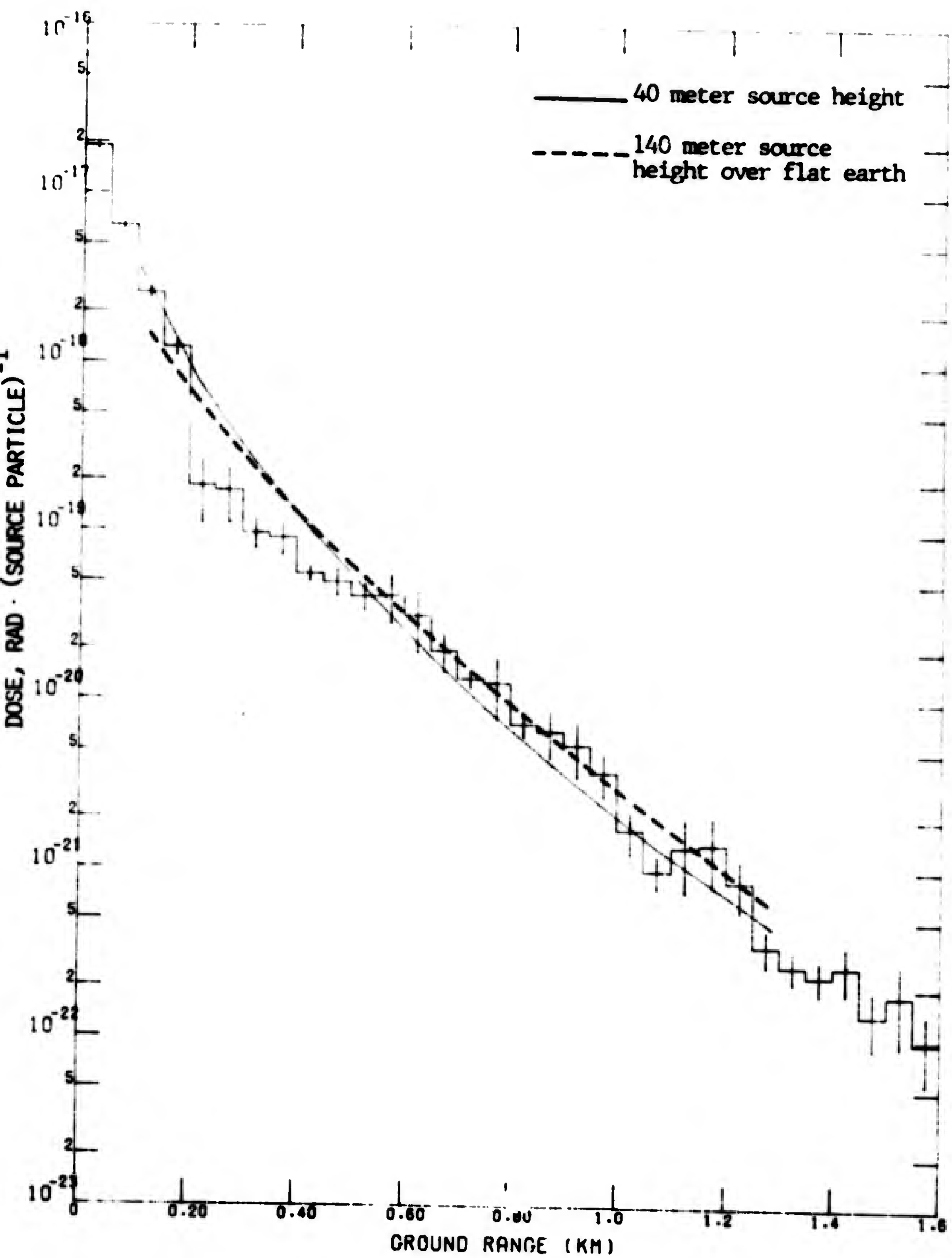


Figure 58. Illustration of source height enhancement effect observed for plateau problem.

Table XVII. Summary of idealized topography results.

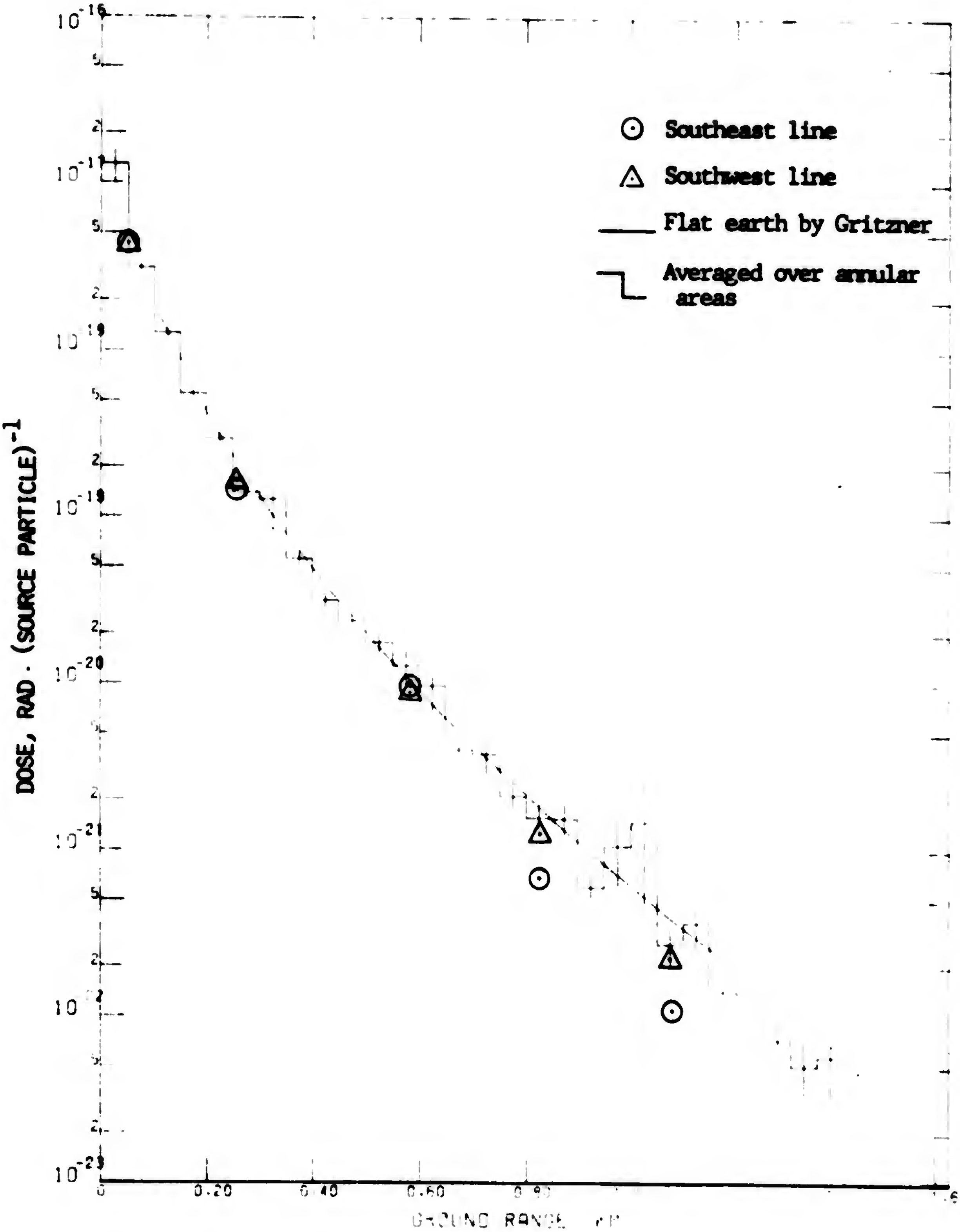
Problem No.	Approximate Attenuation Factor at 1000 Meter Ground Range		Comment
	Tissue Dose	Armor Shielded Tissue Dose	
Valleys			
V1	<1.25	<1.25	15^{o} slope
V2	<1.25	<1.25	30^{o} slope
V3	4.	4.5	45^{o} slope
V4	8.	8.	Same as V3, different source
Hills			
H1	2.5	1.5	high hill, source in valley
H2	1.5	<1.25	intermediate hill in valley
H3	<1.25	<1.25	low hill in valley
H4	1.75	1.5	intermediate plateau in valley
H5	7.	4.	high plateau in valley
H6	3.	2.	intermediate plateau steeper valley
H7	1.5	<1.25	high plateau, source on plateau
H8	.75	.75	same as H7 different source
H9	5.0	4.0	same as H5 different source
H10	1.75	1.5	same as H1 different source
H11	1.75	<1.25	similar to H1, hill further away from source

5.2.2 Real Terrain

In Figures 48 through 53, which show the tissue dose for the three terrain problems averaged over annular rings, no statistically significant terrain effect can be observed. From the understanding gained in the idealized calculations, this result can be anticipated. Where line of sight exists between weapon and target, significant departures from flat ground predictions are not expected for smaller than 15° slopes. In none of the three real terrain problems does the ground slope exceed 15° for any substantial distance. In the first two real terrain problems, the southeast quadrant of the problem is shadowed from the burst by intervening terrain. An examination of the tabulated results for the problem centered about coordinate (40, 17) shows that indeed the tissue dose is approximately a factor of 2 lower behind Hill 322. Figure 59 shows the results of this problem for a southeast line from ground zero up and over Hill 322 and for a southwest line up the Schlitz River valley from ground zero. These results are compared with the flat earth calculations by Gritzner and the calculations in real terrain averaged over annular areas. The peak of Hill 322 is approximately 700 meters from ground zero. The symbols are data points plotted from Table XI for a southeast and southwest line from ground zero. The two points beyond 700 meters ground range show evidence of the shadowing effect of the hill.

5.3 The Effects of Small Bodies of Water

The calculation of the effects of a small body of water shown in Figure 54 should be representative of a burst in the vicinity of a river such as may be found in Central Germany. No statistically significant effect can be observed due to the presence of the body of water. From this calculation and from the observations stated previously in the comparison of air/ground and air/water calculations, it can be concluded that small bodies of water do not significantly effect prompt tissue dose predictions from representative nuclear weapons.



Southeast line
Southwest line
Flat earth by Gritzner
Averaged over annular areas
DOSE, RAD · (SOURCE PARTICLE)$^{-1}$
0.20
0.40
0.60
0.80

6. CONCLUSIONS AND RECOMMENDATIONS

From an analysis of the results of present calculations, several conclusions can be made:

1) The effects of a dense forest on prompt personnel dose are significantly smaller than earlier sources had estimated,

2) Dense forest protection factors are relatively independent of ground range and weapon spectra and range in values from 3 to 1.5 for source heights ranging from 0 to 160 meters,

3) Where line of sight exists between weapon and target, topographical effects can be largely attributed to geometric scaling, based on local terrain features,

4) Terrain protection factors where topography shadows the weapon burst from the target can be as high as a factor of 5 for commonly occurring terrain and a factor of 8 - 10 in isolated situations,

5) Flat earth calculations give reasonable predictions of average dose in real terrain. Pretargeting analysis may take advantage of substantial protection provided by some terrain features,

6) The effects of rivers and lakes are not significant for prompt personnel dose from tactical nuclear weapons.

Several improvements are recommended for future work:

1) Where terrain protection factors are significant, the effect on the neutron dose to gamma ray dose ratio should be determined. The neutron to gamma ray ratio may be an important consideration for predicting biological response. The present calculations considered terrain effects on total prompt dose.

2) An expanded data base of real terrain calculations should be developed for use in developing more sophisticated models of terrain effects,

3) The sensitivities of terrain effects to weapon spectra should be investigated,

4) Real terrain should be classified in terms of generic terrain features so that generic terrain protection factors can be applied to real cases.

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