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CALCULATION OF ISODOSE CURVES FROM INITIAL NEUTRON RADIATION OF A HYPOTHETICAL NUCLEAR EXPLOSION USING MONTE CARLO METHOD

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ABSTRACT

Nuclear explosions are usually described in terms of its total yield and associated shock wave, thermal radiation and nuclear radiation effects. The nuclear radiation produced in such events has several components, consisting mainly of alpha and beta particles, neutrinos, X-rays, neutrons and gamma rays. For practical purposes, the radiation from a nuclear explosion is divided into "initial nuclear radiation", referring to what is issued within one minute after the detonation, and "residual nuclear radiation," covering everything else. The initial nuclear radiation can also be split between “instantaneous” or “prompt” radiation, which involves neutrons and gamma rays from fission and from interactions between neutrons and nuclei of surrounding materials, and “delayed" radiation, comprising emissions from the decay of fission products and from interactions of neutrons with nuclei of the air. This work aims at presenting isodose curves calculations at ground level by Monte Carlo simulation, allowing risk assessment and consequences modeling in radiation protection context. The isodose curves are related to neutrons produced by the prompt nuclear radiation from a hypothetical nuclear explosion with a total yield of 20 KT. Neutron fluency and emission spectrum were based on data available in the literature. Doses were calculated in the form of ambient dose equivalent due to neutrons $H^*(10)_n$.

1. INTRODUCTION

Nuclear explosions release energy in various forms, usually divided into four main groups: shock wave, thermal radiation, initial nuclear radiation and residual nuclear radiation. The proportion of the total received energy at a given distance from detonation and belonging to each group depends on the type of device (fission or thermonuclear), its total yield and the environment in which it occurs [1].

In general, it can be taken as a thumb rule that an air burst at an altitude lower than 12 thousand meters will release 35% of its yield in the form of thermal radiation and 50% will produce the shock wave. The remaining 15% of the energy will be released as initial nuclear radiation (5%), defined as that produced within one minute after detonation, and residual (or late) nuclear radiation (10%), referring to that emitted for some time after the initial nuclear radiation. This last energy fraction is mainly due to radioactive emissions from the decay of fission products. In thermonuclear devices, on the average, each type of reaction (fission and fusion) contributes about half of the energy released[1]. Thus, on these artifacts the residual nuclear radiation accounts for only 5% of the total energy released. Although seemingly lesser extent, the initial nuclear radiation (mainly gammas and neutrons) can travel long distances through the air and cause serious harm to health, besides affecting electronic equipment. Both types of radiation are very penetrating, being imperceptible to human senses (except in high doses). These combined aspects can cause a considerable number of victims, making it a very relevant component in nuclear explosions [1].

In this context, the main objective of this study was to use a radiation transport code based on the Monte Carlo method to simulate the neutron initial radiation field produced in a hypothetical nuclear explosion and calculate the doses due to this type of radiation.

The quantity used to measure the dose was the *Ambient Dose Equivalent* - H*(10), defined as the dose which would be deposited by an expanded and aligned radiation field at a point 10 cm from the surface of the ICRU sphere, in the opposite direction of the radiation field. For this calculation it was necessary to use fluence-to-dose conversion factors provided by ICRP 74 [2].

2. MATERIALS AND METHODS

2.1. Computer modeling

It was used the *Monte Carlo N-Particle eXtended* (MCNPX) code [3] as a tool to create the computational model of this work. The simulated atmosphere consists of layers spaced every 50 meters from ground level up to 600 meters. The density of each layer of the atmosphere was calculated from the *International Standard Atmosphere* [4] by interpolation from values available in the reference. It was considered a soil layer of 1 meter depth below the surface of the ground. Data on chemical composition of the soil and atmosphere were obtained from the literature [5]. Figure 1 shows an image of the system generated by *Vised* code that accompanies the MCNPX code, allowing the identification of the atmosphere and soil layers.

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[1] there may be variations in individual cases like the “boosted” fission weapons [1]

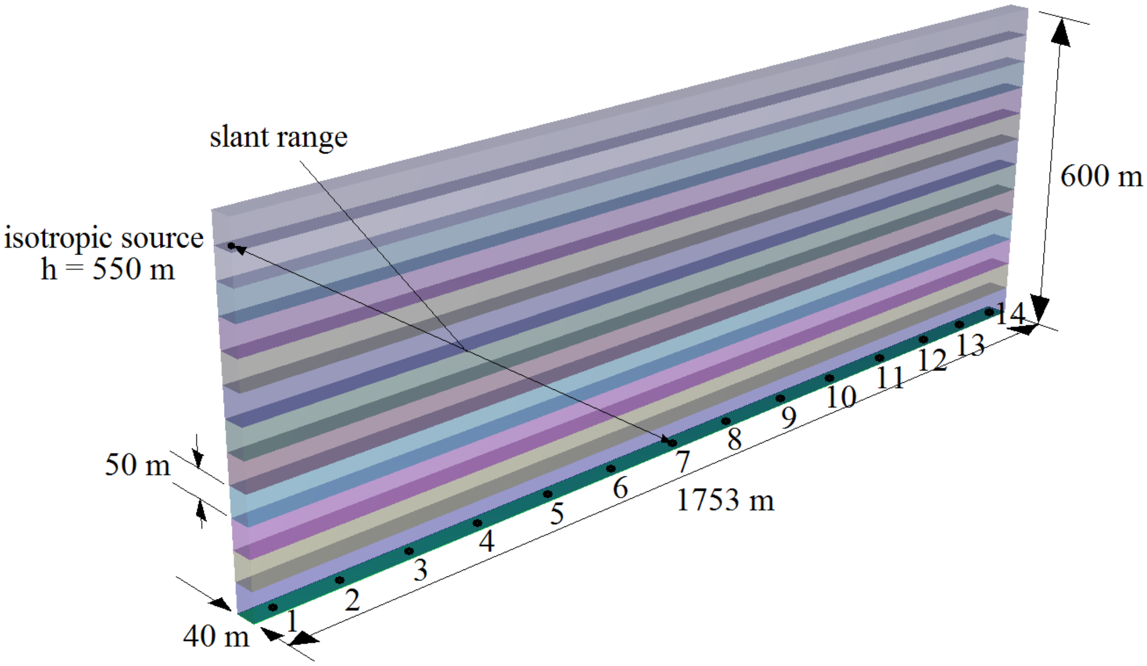

Figure 1: 3D view of the computer model

It was used F5:N tally (*pulse height tally*) to calculate neutron fluxes in simulated point detectors at 14 positions in the ground plane, at each 100 meters of slant range from the source. One detector was also placed on the projection of the source position on the ground (ground zero). The relative position of the detectors is also shown in Fig. 1. It is assumed that, as distances involved are much larger than the dimensions of a nuclear device during its early detonation stage, the source could be considered as a point. The height adopted for the source was 550 meters. The source was defined with a "generic" fission weapon spectrum, shown in Figure 2, also taken from the literature [1].

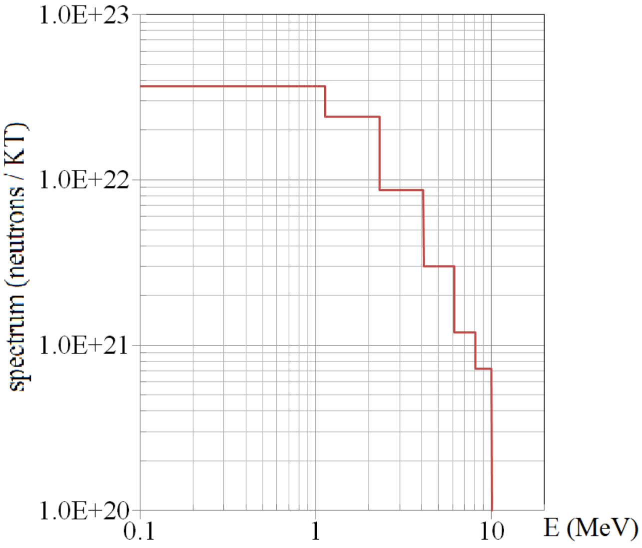

Figure 2: Neutron spectrum for a fission weapon per kiloton total energy yield [1]

Some simplifications were made in order to reduce the computational simulation time. It was assumed that neutrons which crossed vertical planes positioned 20 meters to the left or to the right of the source-detectors plan no longer contribute to the dose. Neutrons that exceeded the altitude of 600 meters were also ignored. In addition, it was assumed that neutrons which penetrate more than 1 meter deep into the soil would be considered "lost" and no longer contribute to the dose on the detectors.

It was considered in this work a hypothetical explosion of 20 kilotons[2] total yield. Computing this yield with the spectrum shown in Figure 2 the source would generate an amount of neutrons of about 1.5E24. This value is consistent with estimates made by other studies [6]. This quantity was used as a multiplicative factor in the computational model, since the default answers to tally F5:N is provided "*per particle emitted*" by the source.

In total, the simulation considered a generation of about 750 million neutrons by the source, resulting in uncertainties lower than 5% in most detectors. All simulations were performed on an Intel core i7 computer with 2.6 GHz, 64-bit.

3. RESULTS, DISCUSSION AND CONCLUSIONS

The results obtained for the doses on each detector are shown in Tab. 1.

Table 1: Ambient Dose Equivalent due to neutrons $H^*(10)_n$ on detectors

Detector	Slant range (m)	H^*10_n (mSv)	Relative error
1	550	2.45014E+05	0.0102
2	600	1.65642E+05	0.0125
3	700	5.70887E+04	0.0145
4	800	2.22127E+04	0.0331
5	900	7.91389E+03	0.0297
6	1000	4.10858E+03	0.1887
7	1100	1.25788E+03	0.0292
8	1200	5.64212E+02	0.0915
9	1300	2.06183E+02	0.0171
10	1400	9.54421E+01	0.0389
11	1500	4.38723E+01	0.0524
12	1600	1.96382E+01	0.0418
13	1700	8.67351E+00	0.0214
14	1800	4.01426E+00	0.0141

Fig. 3, adapted from the literature [1], shows dose calculations in the tissue at or near body surface, due to the initial neutron radiation, in *rads*. One *rad* corresponds to the deposition of 0.01 Joules per kilogram of matter, or 0.01 Gy.

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[2] 1 kiloton (KT) = 1,000 tons of TNT

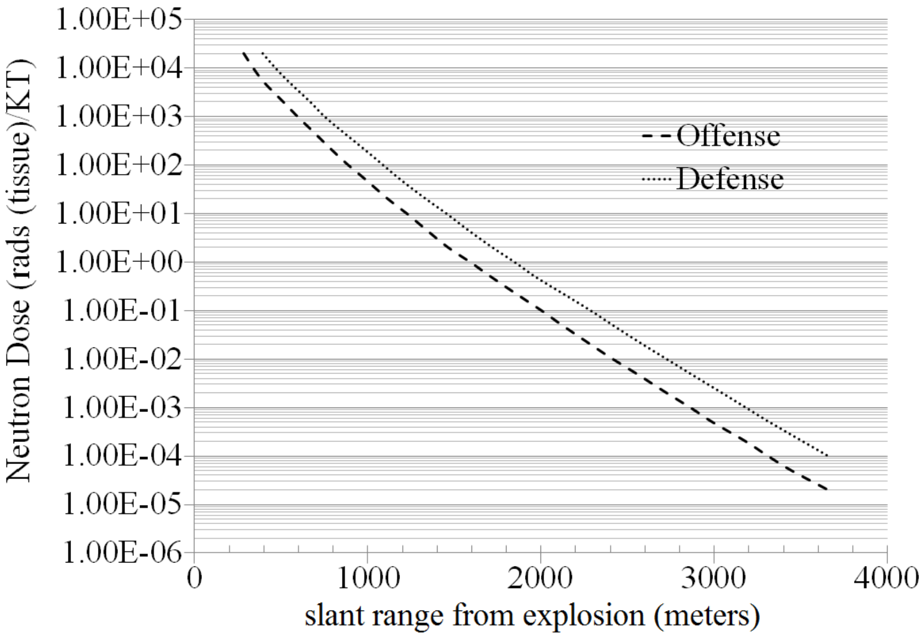

Figure 3: Initial neutron dose per kiloton total yield as a function of slant range from fission weapon air bursts, based on 0.9 normal sea level air density [1]

Based on the graph of Fig. 3, it is possible to estimate neutron doses, in rads, per kiloton, due to a nuclear explosion in the atmosphere, based on an average density of 0.9 of that at sea level. The data presented in Fig. 3 were obtained by calculations and corroborated by experimental measurements. They do not necessarily represent the extremes in neutron doses due to fission artifacts, but the doses of most of these artifacts should fall between those curves. To conservative calculations for defense purposes, the "Defense" curve should be used [1]. To compare the results of Fig. 3 with those obtained in this work it would be necessary to multiply the dose (in rads) by the appropriate quality factor to each of the neutron energy ranges. Quality factors accepted worldwide are defined by the ICRP [2].

The “generic” spectrum of Fig. 2 could also be used for extrapolation and generation of dose curves for different yields as a function of the distance from the burst point. From this spectrum and from the $H^*(10)_n$ values calculated with this computational model, a linear extrapolation using the equation (1) was made to give the graph of Fig. 4. It should be noted, however, that the “real” spectrum is affected by artifact design features. Realistic calculations must take into account each particular case.

$$new\ dose = dose\ per\ particle \cdot \frac{FM_{new\ yield}}{FM_{20\ KT}} \tag{1}$$

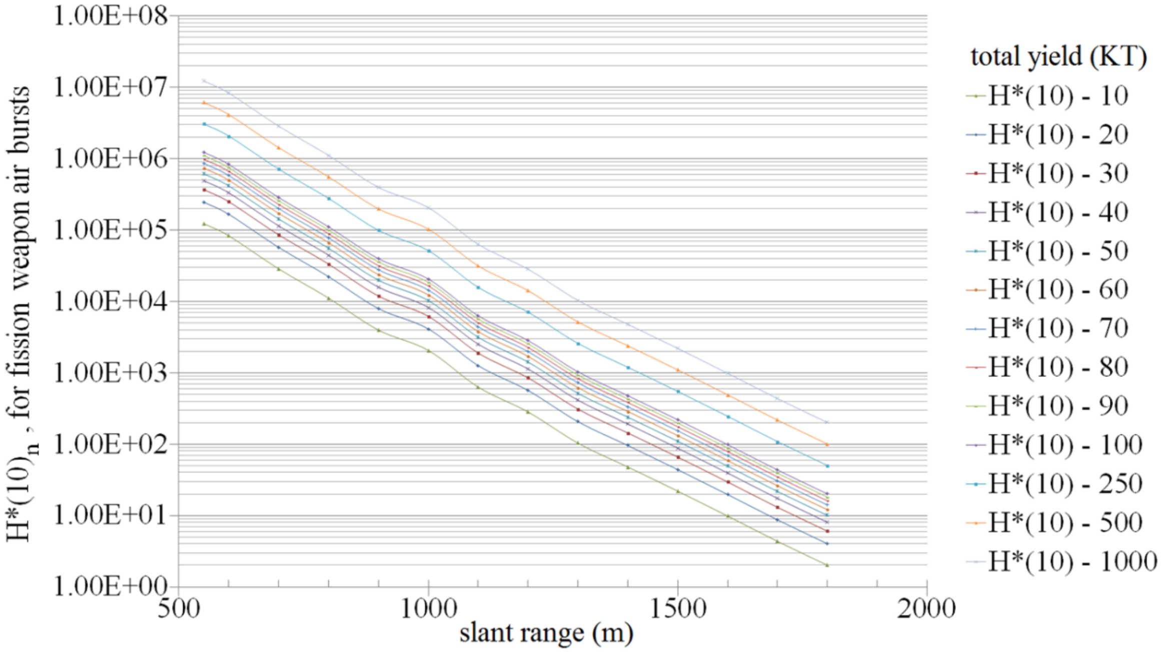

Figure 4: Neutron ambient dose equivalent values for specified total yield, near the ground, as a function of slant range from a 550 m height fission weapon air-burst

Considering the prohibition of atomic explosion tests in the atmosphere, Fig. 4 can be used as a good estimate of the magnitude of $H^*(10)_n$ in the absence of experimental or more accurate data. It should be emphasized that such data refers to air bursts. To be classified this way, a nuclear detonation must occur at an altitude below 30,480 m (100,000 feet[3]) and the "fireball" should not touch the ground surface. The fireball is the intensely hot and luminous mass, roughly spherical in shape, which is formed by the weapon residues mixed with the atmosphere within the first seconds after the detonation. Its diameter can be estimated by equation 2, where R is the maximum radius (in feet) and W is the total yield, in kilotons.

$$R \approx 200W^{0.4} \tag{2}$$

From equation 2, a 20 kiloton fission weapon explosion can be classified as an "air burst" if it takes place at an altitude of at least 200 meters. If the slant range is fixed at 550 meters (the burst altitude) the maximum total yield of an artifact whose explosion should be treated as an "air burst" is approximately 245 kilotons. Thus, for the explosion of fission weapons between 10 and 250 kilotons total yield, it is possible to interpolate values between the given curves in Fig. 4 to obtain the neutron doses.

A contact burst, for most purposes, is defined [1] as one for which the burst point is not more than $5\ \boldsymbol{W}^{0.3}$ feet above the surface. Thus, for a contact surface burst, the dose for a specified explosion yield and range may be obtained upon multiplication of the corresponding dose by a factor of 0.5. For a height of burst between the "contact surface" and about 91.4 meters, the dose may be estimated by interpolation between the value for an air burst and a contact burst [1].

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[3] 1 foot = 0.3048 meter

Doses for explosions between 250 kiloton and 1 megaton[4] can be obtained from Fig. 4 using the aforementioned corrections. Yields beyond 1MT were not considered in this work because it could be considered a thermonuclear weapon range, which have a neutron spectrum very different from that shown in Fig. 2.

It can be seen that the curves of Fig. 4 show the same behavior as those shown in Fig. 3. As expected, there is an exponential decrease of dose with increasing distance due to the low neutron population reaching points increasingly farther. The differences between any values reported in the literature and those obtained in the computational model of this work could be related to several factors such as the approximations made in the system modeling and the different considerations about the atmosphere. Differences in geometry, materials present in the device and / or neutron spectrum are examples of other uncertainties which could affect the results. Moreover, the choice of spatial limits imposed to simplify the problem could also influence the final result.

In conclusion, although there is no data available on $H^*(10)_n$ for comparison purposes, and given the uncertainties mentioned, the obtained computational result is consistent with what was physically expected and with dose data (energy deposited in rads) available in the literature [1]. A more accurate comparison would require performing simulations considering specific details of the design of a given artifact, which is beyond the scope of this work.

In future studies, we intend to investigate the effects of varying the altitude of the source in the deposited dose and also the effect of increasing or decreasing the spatial limits considered. From this information we can assess risks and model consequences in the context of radiological protection. Additionally, it is intended to simulate typical urban scenarios in order to assess the dose due to neutrons within common buildings.

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[4] 1 megaton (MT) = 1,000,000 tons of TNT

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