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PROMPT NEUTRON AND GAMMA DOSES FROM AN ACCIDENTAL CRITICALITY

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Abstract

Equations are developed for estimating doses from prompt neutron and gamma radiations from out-of-core criticality accidents. These equations are intended only for planning and safety analysis purposes. The results are:

$$D_\gamma = 2.1 \times 10^{-20} N X^{-2} e^{-3.4X}$$

$$D_n = 7 \times 10^{-20} N X^{-2} e^{-5.2X}$$

where D_γ and D_n are respectively gamma and neutron dose equivalents (rem), N is number of fissions, and X is distance from the source (km).

Introduction

In many activities involving fissile materials, the possibility of an accidental nuclear chain reaction cannot be completely eliminated. In such instances, prudence dictates that the potential hazards be evaluated and provisions be made for coping with them. This paper presents the development of two equations for use in this evaluation and preparation process.

A quarter-century of experience in processing fissile materials has resulted in seven known out-of-core criticality accidents.[1] In addition, two such accidents were experienced in handling fissile metals. While generalization from such a small number of events is questionable, this

413 173

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experience must be taken into account in hazard assessments. Experience strongly suggests that:

1. Criticality accident programs have been effective;
2. Unless these programs are dramatically relaxed, criticality accidents will continue to be rare;
3. Under present and foreseeable conditions, criticality accidents will present only local hazards; and
4. Radiological hazards from criticality accidents will be dominated by the radiation released during criticality.

The factors controlling direct radiation hazards are interrelated and are not known before the event. The number of fissions is a major consideration because it determines the quantity of radiation generated. Number of fissions, however, is not an independent factor but is largely determined by the mass, material composition, and geometry of the assembly (along with speed of assembly). These same factors control the fraction of radiation that escapes from the assembly and the extent to which the energy is degraded before it escapes. Since these characteristics of the accidental assembly cannot be known in advance, radiation hazards cannot be accurately foretold.

For safety analysis purposes, an accurate prediction of radiation levels is not essential. Safety needs are met if the calculation is conservative without being excessively conservative. The purpose of this paper is to present the development of equations that meet these needs in estimating doses from prompt neutron and gamma radiations.

413 174

Prompt Gamma Doses

In general, when a gamma source and a detector are separated by a distance X and the only shielding is provided by the air, the dose is given by:

$$D_\gamma = N\ E\ L\ (\ \mu a/\rho\ )\ K\ B\ e^{-\mu X}\ /4\ \pi X^2$$

The number of nuclear disintegrations is N, the gamma energy release per disintegration is E (MeV), the self-attenuation factor is L, the energy absorption coefficient of tissue is ($\mu a/\rho$), and K is the dose conversion factor, 1.6×10^{-8} (rem-gm/MeV). In assessing criticality accident hazards, it is generally satisfactory to approximate the attenuation and buildup function with:

$$B\ e^{-\mu X} \approx e^{-\mu a X}$$

The energy absorption coefficient of air is μa.

In the fission process, the gamma radiation released is characterized by a broad spectrum of energies. However, the coefficients are not strong functions of energy so a one-group approximation can be used. For 1 MeV gammas in air, the energy absorption coefficient is given[2] as about 0.026 cm^2/gm; for 0.0013 gm/cm^3 air, this corresponds to 3.4 km^{-1}. The energy absorption coefficient for tissue is 0.03 (cm^2/gm)[3] or 3×10^{-12} (km^2/gm).

For an assembly of sufficient size to sustain criticality, there seems little likelihood that more than 70% of the gamma energy will escape. The self-attenuation coefficient (L) is taken as .7.

413 175

The value for E, the prompt gamma energy per fission, is taken as 8 Mev.[2]

With these values and approximations, the expression for the prompt gamma dose is:

$$D_\gamma = 2.1 \times 10^{-20} N X^{-2} e^{-3.4X} \ldots \text{rem}$$

Neutron Dose

For each neutron absorbed in fissile material, approximately 2 are produced by fission. Thus, for each fission, about one neutron is available to leak out of the assembly and contribute to the radiation field. Experience and reactor physics considerations suggest that no more than one-fourth of these actually escape as fast neutrons. Thus, the neutron source strength is taken as 0.25N, where N is the number of fissions.

At a distance X (km) from the assembly, where X is large compared to the dimensions of the assembly, the fluence will be:

$$\phi = 0.25 N X^{-2} \times 10^{-10} e^{-\Sigma X}/4\pi$$

The removal cross section is Σ and 10^{-10} is the conversion factor between cm^2 and km^2.

Blizzard[2] gives a removal cross section for air of 0.04 cm^2/gm. For 0.0013 gm/cm^3 air, this corresponds to:

$$\Sigma = 5.2 \ (km^{-1})$$

413 176

The relationship between neutron fluence and dose is nearly independent of neutron energy for energies between 1 and 10 MeV. For lower energies, the dose declines with neutron energy. For the present purpose, it is appropriate to use the conversion value for 1 MeV neutrons viz. 19nv gives 2.5 mrem/hr.[4] Thus:

$$D_n = .0025/19/3600\ \phi = 3.7\phi \times 10^{-8} \quad \text{or}$$

$$D_n = 7 \times 10^{-20}\ N\ X^{-2}\ e^{-5.2X} \ \ldots \text{ rem}$$

Discussion

As noted earlier, these simple expressions cannot be accurate. The fraction of both the neutron and the gamma radiation that escapes is largely determined by the size, shape, and composition of the assembly. These factors cannot accurately be taken into account when predicting criticality accidents.

Comparison to the dose data from actual criticality accidents[5] suggests that these expressions may be conservative for larger events, such as are likely to be assumed in safety analyses, but may be unconservative for smaller accidents. For example, these equations slightly overestimate the doses from the Y - 12 accident while underestimating the Wood River Junction doses.

Others have developed equations similar to these. The UK Atomic Energy Authority[6] uses essentially the same coefficient for gamma dose, and their value for total dose is only 34% lower than the present results.

413 177

Thus, it seems that these results are conservative without being excessively conservative.

Other expressions that have been proposed for assessing prompt radiation doses from criticality accidents have not included the air attenuation function. For most purposes, air attenuation can be safely ignored. It is included here to avoid the implication that a criticality accident might produce a large cumulative (man-rem) dose.

The expression for neutron dose includes a quality factor (QF) that is appropriate for chronic radiation effects. This expression is not appropriate for predicting acute lethal effects. The QF is defined only for doses on the order of those deemed maximum permissible by the International Commission on Radiological Protection. Generally, it is recognized that, for acute lethality, the appropriate value would be between 1 and 3. If the value of 3 is used, this would reduce the neutron dose coefficient by a factor of 3 and put these results in agreement with Paxton who predicts doses in the lethal range at 10 feet from 10^{17} fissions.(1)

Conclusion

The equations developed here should provide estimates of prompt gamma and neutron doses that are adequate for safety analysis purposes provided their limitations are recognized. The principal limitations are:

413 178

1. The neutron dose estimate should be reduced by a factor of 3 for acute lethality assessments.

2. These expressions may underestimate the consequences of accidents involving small assemblies.

3. These expressions do not provide the accuracy available with more detailed calculations utilizing information about the specific event under consideration.

References

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