The Calculation of Dose to Externally Contaminated Livestock and Animal Triage for Livestock Handling and Processing

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Abstract

Nuclear or radiological events or the malevolent use of radioactive material may result in a significant release of radioactive materials to the environment. The contamination of livestock animals in agricultural areas in close proximity to the release site may cause significant technical, logistic, and economic difficulties for the affected region.

Rapid and effective response to a large amount of contaminated agricultural products, such as livestock, by the Competent Authority will require a prepared and effective plan for handling and processing of these products. A protocol outlining the evaluation of and procedures for handling and processing radioactively contaminated livestock has been developed, to ensure safe animal food production and economic stability in the livestock industry in the wake of such a nuclear or radiological event. An evaluation of the salvageability of the contaminated livestock has been performed based on the degree of exposure, the cost of decontamination, expected demand for food products, and economic impact to the owner / producer, in order to serve as a basis for animal triage for the further handling and processing of affected livestock.

As salvageability is defined in terms of dose to the animal, a mathematically rigorous formalism to assess the animal dose has been developed. The general approach outlined in ICRP 108 is used for the mathematical description of the relevant exposure and contamination scenarios.

Key Words: external dosimetry, animal dose, emergency preparedness, emergency response, agricultural products

Introduction

After a nuclear or radiological event, the external radioactive contamination of livestock is a local and potentially global concern. The Chernobyl reactor accident contaminated livestock in the direct vicinity leading to difficulties in the management of handling and disposal of the animals. Unnecessary slaughtering of the animals due to fears of economic loss complicated the management process by increasing radiological waste and health concerns due to the carcasses (IAEA 2006). This was done without accounting for the substantial cost associated with radiological waste disposal. Current emergency plans do not address an economically efficient process for the management of contaminated livestock.

Previous studies have shown that corrective actions to minimize radioactivity levels in the food chain following a nuclear event are reasonably accepted by the farmers (Grande et al. 1999). However, there are limited data on consumer concerns on the adequacy of countermeasures. Studies performed in Norway and Scotland following the Chernobyl accident focused on consumer risk attitudes and behavior toward food affected by radioactive contamination. Analyzing consumer risk is complex and consists of several variables dependent upon individual beliefs (Grande et al. 1999). Although data is limited, inferences of consumer acceptance of the countermeasures tend to increase when the plans address socioeconomic factors (IAEA 2006). Therefore, emergency plans for the handling of contaminated livestock should address these socioeconomic factors. This paper addresses animal salvageability based on animal dose, cost of decontamination, expected demand for food products, and economic impact to the owner.

Determining the dose to the animal can be difficult since there is minimal data concerning radiation dose and effects to biota. The International Commission on Radiological Protection (ICRP) recognizes the need for more science addressing biota radiation effects and dose determination (ICRP 2008). Therefore, the ICRP has developed the concept of Reference Animals and Plants in order to obtain consistent results of dose and dose effect. Using simple geometries and computer source modeling, the ICRP developed and lists dose conversion factors in ICRP 108 relating activity concentration to absorbed dose.

Since this paper addresses concerns for livestock, the focus will be on the adult deer which the ICRP has chosen to represent large mammals. Animal shapes differ amongst species which can cause difficulty in dose calculations. Thus simple geometric figures such as the solid sphere, cylinder, and ellipsoid were chosen to model the reference animals (ICRP 2008). The simple geometries are vastly different when compared to the human anthropomorphic phantoms which mimic human anatomy, but the ICRP believes that simplification of the geometry will have value for dose determination. The analytic approach outlined here uses the simplified geometries the ICRP has decided to employ for animal dosimetry purposes.

Methods and Materials

A literary review of scientific studies, national and international recommendations, and lessons learned following radiological exercises was conducted to determine a plan for the handling of contaminated livestock. The key to this plan is determining the salvageability of an animal, providing reference levels for the humane treatment of affected livestock, as well as protecting the consumer. The decision level for processing an animal or requiring an animal to have further evaluation is estimated based on the absorbed dose.

Dose determination from first principles employs the following equation:

$$\dot{D} = \frac{AE}{4\pi d^2}\left(\frac{\mu_{en,m}}{\rho_m}\right), \tag{1}$$

where A represents the activity at a distance d from the point of the dose rate measurement, E is the incident photon energy, and $\mu_{en,m}$ and ρ_m are the linear energy absorption coefficient and the density for the medium m respectively. This equation does not yet include buildup in the material and attenuation between the source and the target. To account for these factors, Equation 1 needs to be expressed as:

$$\dot{D} = \frac{1}{4\pi}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \frac{1}{V}\int_V \frac{B(\mu D_m)e^{-\mu D_m}}{d^2}\, dV, \tag{2}$$

where μ is the linear attenuation coefficient in the material, D_m is the distance from the surface of the animal to the volume element, dV, and $B(\mu D_m)$ is the buildup factor as a function of the number of relaxation lengths, μD_m, along the path of photon travel in the material.

The simple geometric shapes used to describe reference terrestrial mammals defined by the ICRP (ICRP 2008) can be used to define d, D_m, dV, and the volume integration limits. Depending on the geometry, the values for the variables are transformed depending on the coordinate system of choice in order to more easily solve the integrand. Analytical expressions have been derived for solid spheres, solid prolate ellipsoids, and solid ellipsoids with minor axes of unequal length. The coordinate systems of choice are spherical coordinates, prolate ellipsoidal coordinates, and ellipsoidal coordinates, respectively.

The buildup factor, $B(\mu D_m)$, has not been evaluated any further and needs to be determined from tabulated data for the target material (i.e., tissue) under consideration.

Results and Discussion

The decision level for determining whether an animal is salvageable is that species' absorbed dose at which 90% of the individuals exposed are expected to survive (LD_{10}). Animals with doses below the LD_{10} are not expected to display any observable symptoms which would provide grounds for immediate disposal (Berger et al. 1987). Reviews of animal studies estimated the LD_{50} for large animals between 1.50 Gy and 2.65 Gy and smaller animals between 5.40 Gy and 15.2 Gy (Bond and Robertson 1957; Carsten 1984). Livestock animals generally consist of cattle, pigs, sheep, and goat. Cattle most certainly fall under the large animal group and although the latter animals are much smaller, their LD_{50} data were specifically provided and coincide with the large animal group. Use of the LD_{50} value as a decision level is not useful since half of the population is expected to succumb to acute radiation injury. Therefore, the decision level is determined to be at the onset of noticeable deterministic effect based on human data.

Human estimates of the LD_{10} vary from 0.865 Gy to 5.87 Gy in various studies (Anno et al. 2003). A high expectancy of human survival from an acute whole body radiation exposure of approximately 1 Gy coincides with their LD_{10}. At this level of absorbed dose, individuals might already present with the hemopoietic syndrome, exhibiting the earliest symptoms of acute radiation sickness. This assessment is supported by Chernobyl data in which no acute adverse effects were observed below doses of 0.3 Gy (IAEA 2006). A decision level of 1 Gy for large animals is a good estimate, but not for small animals. Since the LD_{50} range for small animals is about two times greater than for large animals, and for poultry it is about three times greater, doses below 2 Gy and 3 Gy are suggested as salvageability levels for small animals and poultry, respectively.

The cost of decontaminating an animal has not been well characterized since there is minimal data on effective animal decontaminating techniques. Different methods of animal decontamination are currently under investigation. The cost of disposing of a contaminated carcass is estimated at about $8,000 whereas the market price for cattle can vary in the range of $0.80 to $1.20 per pound (McMillan et al. 2011). An animal deemed salvageable may have decontamination costs that exceed the cost of disposal.

The food demand depends greatly on the public's willingness to purchase livestock products that were in the contaminated area but are deemed safe for consumption. The public's perception of the situation can vary in time and the Competent Authority must use sound judgment at that specific moment to determine how to present these livestock products to the public. Public perception is difficult to measure and the few studies performed used surveys to acquire a snapshot of the public's discernment (Grande et al. 1999).

Even if the food is placed in the market, consumers may not purchase it due to the fact that the animals were in the vicinity of the radiological event or that there is an abundance of alternative food products. Besides disposal of the animal, a more economical choice for the livestock owner would be to sell the products to a secondary market such as animal feed or leather goods, or donating the products to other users such as zoos (McMillan et al. 2011).

As we define salvageability and the potential for further livestock processing options on the basis of absorbed dose, the dose to the animal has to be assessed. Three geometries consisting of a sphere, prolate ellipsoid, and general ellipsoid were chosen for consistency with the ICRP. Converting Equation 2 to the correct coordinate system for the geometry and analyzing it yields the following results for an external source:

Sphere

$$\dot{D} = \frac{3}{16\pi^2 R^3}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_0^R \int_0^\pi \int_0^{2\pi} \frac{B(\mu D_m) e^{-\mu D_m} r^2 \sin(\theta)}{r^2 + (h+R)^2 - 2r(h+R)\cos(\theta)} \, d\varphi \, d\theta \, dr$$

(3)

Prolate Ellipsoid

$$\dot{D} = \frac{3}{16\pi^2 m_1 m_2^2}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_0^{\mu_{max}} \int_0^{\pi} \int_0^{2\pi} \frac{B(\mu D_m)\, e^{-\mu D_m} (m_1^2 - m_2^2)^{3/2} (\sinh^2(\mu) + \sin^2(v)) \sinh(\mu) \sin(v)}{(m_1^2 - m_2^2)(\sinh^2(\mu) + \cos^2(v)) + 2\sqrt{m_1^2 - m_2^2}\,(m_2 + h)\cosh(\mu)\cos(v) + (m_2 + h)^2}\, d\varphi\, dv\, d\mu$$

(4)

General Ellipsoid

$$\dot{D} = \frac{3}{16\pi^2 abc}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_{-c^2}^{a^2} \int_{-b^2}^{-c^2} \int_{-a^2}^{-b^2} \frac{B(\mu D_m)\, e^{-\mu D_m} (\lambda - \mu)(\mu - v)(\lambda - v)}{8\sqrt{-(a^2+\lambda)(b^2+\lambda)(c^2+\lambda)(a^2+\mu)(b^2+\mu)(c^2+\mu)(a^2+v)(b^2+v)(c^2+v)}}\, dv\, d\mu\, d\lambda$$

(5)

If the radioactive source is contamination on the surface of the animal, then the distance from the source to the animal, *h*, approaches zero. Since the distance the photons travel in air is 0, $D_m = d$ and taking the limit of *d* as *h* approaches zero results in the following equations:

Sphere

$$\dot{D} = \frac{3}{16\pi^2 R^3}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_0^R \int_0^{\pi} \int_0^{2\pi} \frac{B(\mu d)\, e^{-\mu\sqrt{r^2+R^2-2rR\cos(\theta)}}\, r^2 \sin(\theta)}{r^2 + R^2 - 2rR\cos(\theta)}\, d\varphi d\theta dr$$

(6)

Prolate Ellipsoid

$$\dot{D} = \frac{3}{16\pi^2 m_1 m_2^2}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_0^{\mu_{max}} \int_0^{\pi} \int_0^{2\pi} \frac{B(\mu d)\, e^{-\mu d} (m_1^2 - m_2^2)^{3/2} (\sinh^2(\mu) + \sin^2(v)) \sinh(\mu) \sin(v)}{(m_1^2 - m_2^2)(\sinh^2(\mu) + \cos^2(v)) + 2\sqrt{m_1^2 - m_2^2}\, m_2 \cosh(\mu)\cos(v) + m_2^2}\, d\varphi\, dv\, d\mu$$

(7)

General Ellipsoid

$$\dot{D} = \frac{3}{16\pi^2 abc}\left(\frac{\mu_{en,m}}{\rho_m}\right) AE \int_{-c^2}^{a^2} \int_{-b^2}^{-c^2} \int_{-a^2}^{-b^2} \frac{B(\mu d)\, e^{-\mu d} (\lambda - \mu)(\mu - v)(\lambda - v)}{8\sqrt{-(a^2+\lambda)(b^2+\lambda)(c^2+\lambda)(a^2+\mu)(b^2+\mu)(c^2+\mu)(a^2+v)(b^2+v)(c^2+v)}}\, dv\, d\mu\, d\lambda$$

(8)

For the general ellipsoid, the singularities in the integrand are at the integration limits which may result in diverging numerical values unless appropriate numerical margins are introduced in order to bound the integral to the finite domain. The use of a more sophisticated definition of the effective bounds on the integral expression is currently under investigation.

Conclusions

The salvageability of livestock following a nuclear or radiological event is based on the animal's exposure, cost of decontamination, expected demand for food products, and economic impact to the owner/producer. Doses at 1 Gy or less deem large animal livestock as salvageable and doses for small animals and poultry are 2 Gy and 3 Gy respectively.

A complete analytical approach has been derived to calculate the absorbed dose to terrestrial animals based on the sphere, prolate ellipsoid, and general ellipsoid geometries suggested for reference animals (ICRP 2008). Dose rate equations have been developed for external sources and surface sources to allow a direct evaluation of the dose to the animal for use in triage.

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