Chernobyl Wildfire Project Report on Model Methodology

Author

Andrew Niccolai, Ph.D.

Project Members

Chad Oliver, Ph.D.

Sergiv Zibtsev, Ph.D.

Johann Goldammer, Ph.D.

John Wargo, Ph.D.

George Chopivsky, Jr.

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Model Scope

On April 26, 1986, a chain reaction occurred in the Chernobyl nuclear power plant facility that resulted in a series of explosions in reactor No. 4 which released approximately 1.85×10^{18} Becquerel (Bq) of radioactive material into the surrounding environment (Othman 1990). At present, the main hazards to environmental health are considered to be Cesium 137 (^{137}Cs) and Strontium 90 (^{90}Sr) as these radioactive materials have relatively long half-lives and were widely deposited across Europe (Othman 1990). The model described in this report was designed to assess the potential impact of discharges of ^{137}Cs and ^{90}Sr to the environment. Specifically, this report offers an objective assessment of the implications to the population surrounding the Chernobyl nuclear facility under a scenario in which the 30 km Exclusion Zone around Chernobyl were to burn because of a catastrophic wildfire.

The implications to the population are reported as the average *dose* of radioactive materials that is absorbed by a *critical population* during a catastrophic wildfire event in the Chernobyl Exclusion Zone (CEZ). Dose is considered a measure of energy deposited by radiation within a human target and is reported here as the average Sieverts per event (Sv/e). The critical population consists of the members of the public which share a relatively homogenous set of exposure pathways and typically are considered to receive the highest levels of effective dose from a given source of radiation. Reporting the average dose exposure using a critical population constraint forces the model to err on the conservative side as the majority of individuals within a given population will not receive the highest levels of exposure for all possible existing exposure pathways.

The model chosen for this assessment was based on the generic model for use in assessing the impact of discharges of radioactive substances to the environment described in the International Atomic Energy Agency (IAEA) 2001 Safety Report Series (SRS) Number 19. This generic model was selected because it offered a simplified and conservative assessment of the likely magnitude of a radioactive impact on a population. The model as described in the SRS No. 19 manual was intended for use in determining population dose impacts from prolonged or continuous releases into the environment when it is reasonable to assume quasi-equilibrium has been established between released radionuclides and relevant environmental components. This model has been modified for the application of short period release simulations, as would be expected in a catastrophic wildfire, and all modifications to the original IAEA model will be highlighted in the discussion below.

Model Assumptions

In order to assess the potential implications of radioactive material dispersion to the environment surrounding the Chernobyl nuclear facility in the event of a catastrophic wildfire, assumptions must be made for the model selected. The spatial model used in this report and described in detail in *Model Mechanics* was purposefully designed to represent a parsimonious abstraction of radioactive movement throughout an isotropic environment. The reduction in the number of model parameters was intended to provide more transparent understanding behind the mechanics of radiation dispersion and subsequent exposure.

In order to maintain a parsimonious model, several assumptions were incorporated into the design of the model.

- The foliar biomass and forest floor for the area impacted by the catastrophic wildfire event were assumed to be completely eviscerated and therefore any stored radioactive ^{137}Cs and ^{90}Sr were considered available for dispersion to the environment. This assumption is supported as complete removals of duff and foliar biomass in catastrophic wildfires have been noted in studies by Miyanishi and Johnson (2002) and Laughlin *et al*. 2004.
- ^{137}Cs and ^{90}Sr were the only two radioactive materials utilized in this model.

- A five day time horizon was considered for the catastrophic wildfire event in which the 30 km zone surrounding the Chernobyl nuclear facility was simulated to burn.
- Over the five day time period for the wildfire event, the wind was assumed to blow for an equal speed and duration in all geographic quadrants resulting in an isotropic spatial coverage of ^{137}Cs and ^{90}Sr transportation originating from the CEZ and moving out in concentric rings (**Fig. 1**).
- The model further assumes that the critical population remains exposed for the duration of the radioactive release period and therefore individuals that leave the exposed areas will not accumulate as much external and internal exposure as the population for the same period.
- Finally, the individual parameters such as radioactive half life or effective dose from cloud immersion for the radioactive ^{137}Cs and ^{90}Sr elements were taken from the tables of values provided by the peer reviewed IAEA SRS No. 19 manual freely available to the public.

Model Data

Estimates on the amount of ^{137}Cs and ^{90}Sr available in the CEZ were needed to populate the model. McGee *et al*. (2000) reported that 87% of the detected ^{137}Cs in the forests of Sweden were found in the soils while 13% were found in the aboveground biomass. This approximate proportion of ^{137}Cs found in soil to ^{137}Cs found in vegetation was utilized in the estimation process for ^{137}Cs and ^{90}Sr found in the CEZ. The estimates of ^{137}Cs and ^{90}Sr found in the soils of the 30 km zone around Chernobyl were derived from data presented by Kashparov *et al*. (2001). The Kashparov article reported that approximately 8.1×10^{14} Bq of ^{90}Sr was determined to be in the CEZ based on an extensive grid of soil samples taken in 1997. A relationship for ^{137}Cs to ^{90}Sr in the CEZ soils was given as ^{137}Cs was found to be 1.87 times more abundant in the soils than ^{90}Sr with an r^2 of 0.43. Adjusting the soil estimates from the year of the soil survey to the year 2010 using the anticipated decay rate for ^{90}Sr with a half life of 28.8 years resulted in an estimated amount of ^{90}Sr found in the CEZ soils to be 6.1×10^{14} Bq. The amount of ^{137}Cs estimated for the CEZ soils in 2010 was then calculated as 1.1×10^{15} Bq.

A forest biomass inventory provided by the National University of Life and Environmental Sciences of Ukraine for the CEZ was utilized to estimate the percentage of land cover considered to contain forested vegetation. Approximately 40% of the CEZ was considered to contain a substantial above ground biomass component similar in structure to that reported in McGee *et al*. (2000). Therefore, assuming a quasi-equal distribution of radioactive material in the soils as compared with the area of forest cover, approximately 3.7×10^{13} Bq of ^{90}Sr and 6.8×10^{13} Bq of ^{137}Cs were estimated to preside in the vegetative component of the forests within the CEZ. The final estimation of total radioactive material available for transport in the event of a catastrophic wildfire was estimated as 6.4×10^{14} Bq of ^{90}Sr and 1.2×10^{15} Bq of ^{137}Cs in the year 2010.

Model Mechanics

The spatial model utilized in this study provides a systems-based simple screening approach for assessing the average dose potential to those members of a population likely to be most exposed to radioactive materials. In this regard, the assessment is intended to be comprehensive in describing all possible major pathways of radiation exposure and purposefully conservative, reporting risk for cases that involve maximum exposure potential. Transport of the discharged materials is considered through the atmosphere and surface water and exposure pathways for external and internal mechanisms are systematically traced for population level risk assessments. The modified model used in this report is intended to assess the maximum periodic dose received due to combinations of inhalation, immersion, ingestion of food and water and exposure to ground and sediment concentrations. A conservative approach to account for exposures from multiple pathways is to sum up the individual pathway contributions but in reality it is unlikely that any one individual would receive maximum exposure to all possible exposure pathways. An overview of the systems-based modeling approach and the parameters used to assess the impact of a wildfire in the CEZ are given in **Fig. 2**.

Radionuclide Discharge

The first step in modeling the potential impact of a catastrophic wildfire on the transport of radioactive material to the environment is to consider the discharge mechanisms after the ^{137}Cs and ^{90}Sr is volatilized. There are two primary means of transporting radioactive material through the environment, atmospheric and surface water discharge. The rate of atmospheric discharge (Q_i), measured in Bq/s, was calculated as the total amount of ^{137}Cs (and then later ^{90}Sr[1]) for the year 2010 divided by the time period of the wildfire event (sec). The dispersion of atmospheric discharge, or the average air concentration during the event (C_A) measured in Bq/m^3, was calculated as follows:

$$C_A = \frac{P_p F Q_i}{u_a} \qquad [1]$$

where

C_A is the ground level air concentration at downwind distance *x* in sector *p* (Bq/m^3),

P_p is the fraction of time per event that the wind blows toward the target population in sector *p*,

F is the Gaussian diffusion factor[2] appropriate for a given release height and downwind distance *x* (m^{-2}),

Q_i is the average discharge rate per event for radionuclide *I* (Bq/s),

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[1] The spatial modeling reported in this study analyzed the impacts of ^{137}Cs and ^{90}Sr separately and then combined the results of the total dose exposure for each radioactive material at the end. Unless specifically noted, the mechanism of the model will be described for ^{137}Cs and only parameter for ^{90}Sr that are different than ^{137}Cs will be explicitly reported.

[2] The Gaussian diffusion factor formula is given on page 18 of the IAEA SRS No. 19.

u_a is the geometric wind speed average at the area of release representative of the duration of event (m/s).

The second means of transporting radioactive material through the environment includes dispersion through surface water discharge. The periodic average water concentration (C_W) for ^{137}Cs in the event of a catastrophic wildfire was calculated assuming that the Kiev Reservoir was exposed to atmospheric deposition of radioactive material. The nature of the catastrophic wildfire eliminated any need to calculate direct discharge of either ^{137}Cs or ^{90}Sr into the surface water. The water concentration based on only atmospheric deposition of radioactive materials was calculated as follows:

$$C_W = \frac{Q_i'}{q_r + L_i V} \qquad [2]$$

where

C_W is the total radionuclide concentration in water (Bq/m^3),

q_r is the average rate of inflow in the lake (m^3/s),

L_i is the radioactive decay constant (s^{-1}),

V is the estimated volume of the water body (m^3),

Q'_I is the average discharge rate for radionuclide *i* (Bq/s) that assumes no direct discharge into water, calculated as: $Q_i' = \frac{3A_l d_i}{86400}$ [3]

where

A_l is the surface area of the lake (m^2),

d_i is the daily deposition rate of a radionuclide *i* from the atmosphere on the water surface ($Bq/m^2/d$).

Radionuclide Pathways

Once the discharge and consequent dispersion mechanisms are adequately modeled, the potential pathways for critical population exposure can be mapped. The exposure pathways chosen for this model included: inhalation, plume immersion, exposure to ground deposits and ingestion of foodstuffs. Note that the model used in this report does not consider exposure to water borne sediments because the effects of sedimentation are typically limited to the banks containing surface water. It should be noted that the dose estimations in this report might underestimate critical population dosage for personnel that live and work on the banks of the Kiev Reservoir.

Inhalation:

The internal dose from an intake of radioactive material into the body following inhalation depends in part on the age and metabolism of the individual as well as the physicochemical behavior of the radionuclide under consideration. This study differentiates only between infants and adults in terms of significant differences in dose coefficients and inhalation rates. Assessments of more detailed population demographics would ideally utilize intakes and effective dose coefficients appropriate to the ages and physiological profile of the constituent groups under consideration. The effective dose from inhalation for both adults and infants after exposure to radionuclide transportation from a catastrophic wildfire in the CEZ were calculated as follows:

$$E_{inh} = C_A R_{inh} DF_{inh} \quad [4]$$

where

E_{inh} is the periodic effective dose (Sv/e),

C_A is the radionuclide concentration in the air obtained from Equation [1] (Bq/m^3),

R_{inh} is the inhalation rate (m^3/e),

DF_{inh} is the inhalation dose coefficient (Sv/Bq).

Immersion:

Calculations of the effective dose from immersion in the atmospheric discharge plume are based on the semi-infinite cloud model which assumes that radiation from the plume cloud is in a state of radiative equilibrium, inferring that the energy absorbed by a given volume within the cloud is the equivalent of that energy emitted by the same cloud volume. This model has been widely used and includes provisions for partial shielding of the plume cloud by impervious surfaces such as the side of a building. This model did not incorporate the effect of buildings to ensure that the critical population represents the highest risk group possible. In practice, most individuals will not remain exposed to a plume cloud for the duration of the wildfire event but given the potential of certain groups to act in the capacity of fire fighting and emergency first response personnel, it is a reasonable assumption for generic purposes. The effective dose from immersion in the atmospheric plume is calculated as follows:

$$E_{im} = C_A DF_{im} O_f \qquad [5]$$

where

E_{im} is the effective dose from immersion (Sv/e),

C_A is the radionuclide concentration in the air obtained from Equation [1] (Bq/m^3),

DF_{im} is the effective dose coefficient for immersion (Sv/e per Bq/m),

O_f is the fraction of the event for which the critical population is exposed to this plume.

Ground Deposition:

In order to calculate the effective dose from ground deposition during the period of a catastrophic wildfire event, the total daily deposition rate on the ground from both dry and wet processes for a given radionuclide *i* must first be determined along with the estimated concentrations of radionuclides on the ground surface area. For this model, it was assumed that the ground surface was represented by an infinite plane source upon which all radionuclide deposition activity was uniformly distributed. For extremely long lived radionuclides or for terrain that is highly variable, a method to track migration down through a soil column should be considered. A number of models exist that attempt to predict this downward movement but there is very little experimental data available on limited radionuclides and soil types to validate these predictions. For this study, the infinite plane model for estimating the dose from ground deposition was chosen because of the limited duration of the wildfire event for downward migration of radionuclides and the lack of experimental data on ^{137}Cs and ^{90}Sr on the soils surrounding Chernobyl. The effective dose from ground deposition was calculated as follows:

$$E_{gr} = C_{gr} DF_{gr} O_f \qquad [6]$$

where

E_{gr} is the effective dose from ground deposition (Sv/e),

DF_{gr} is the dose coefficient for exposure to ground deposits (Sv/e per Bq/m^2),

O_f is the fraction of the event for which the critical population is exposed to this pathway,

C_{gr} is the deposition density of radionuclide *i* (Bq/m^2), calculated as:

$$C_{gr} = \frac{d_i[1-e^{-L_{E_i^s} t_b}]}{L_{E_i^s}} \qquad [7]$$

where

t_b is the duration of the discharge of radioactive material (d),

$L_{E_i^s}$ is the effective rate constant for reduction of the activity in the top layer of the soil (d^{-1}), calculated by adding the radioactive decay constant for radionuclide *i* with the rate constant for reduction of soil activity owing to processes other than radioactive decay,

d_i is the total ground deposition rate (Bq/m^2/d), calculated as:

$$d_i = (V_d + V_w)C_A \qquad [8]$$

where

V_d is the dry deposition coefficient for a given radionuclide *i* (m/d),

V_w is the wet deposition coefficient for a given radionuclide *i* (m/d),

C_A is the radionuclide concentration in the air obtained from Equation [1] (Bq/m^3).

Ingestion of Foodstuffs:

The food chain models assume that the critical population is exposed to radionuclides through ingestion of vegetation, meat, milk, and fish products that have been part of the transfer process of either the atmospheric or surface water discharges. Radionuclides intercepted and preserved by vegetation may result from deposition from atmospheric fallout, precipitation rainout or irrigation with contaminated water. A percentage of these external deposits become internalized to the vegetation through foliar absorption or root uptake. Radioactive decay, growth dilution, non-contaminated water wash off and soil fixation are all processes that can eventually lead to reductions in the radionuclide concentration within vegetation. These processes require longer time horizons than the wildfire event scenario described in this paper and therefore will not be included in the model for dose from plant ingestion. The intake of radionuclides by animals depends on the size, species, age, feed material and milk yield. For this study, it was assumed that the meat from animals originated as cattle byproducts and that the cattle grazed only on fresh pasture during the grazing season. The concentration of radionuclides in the milk was depended upon the radioactivity concentration in the feed consumed by the milk producing animals. This study used the values recommended by the IAEA SRS No. 19 specific to dairy cows; however, they are also applicable to other lactating animals without significantly underestimating the radioactive concentration in those milk products. The concentration of radionuclides in fish depends on the bioaccumulation through various trophic levels of aquatic life in contaminated water. While the trophic level of the organism is the most critical component of the bioaccumulation of radionuclides, other contributing factors include the amount of suspended sediment, the chemical composition of the water, the characteristics of the radionuclide and the characteristics of the aquatic organism under consideration. This study uses bioaccumulation values that ensure a conservative estimate of the transfer of dissolved radionuclides from water to edible aquatic organisms. Much like the rates of atmospheric inhalation, the ingestion of vegetation, meat, milk, and fish is highly variable within population demographics. This study differentiated between adult food consumption and infant consumption.

The general calculation of the periodic effective dose from consumption of radionuclide *i* in foodstuff *p* is as follows:

$$E_{ing,p} = C_{p,i} H_p DF_{ing} \qquad [9]$$

where

$E_{ing,p}$ is the effective dose from consumption of radionuclide *i* in foodstuff *p* (Sv/e),

H_p is the consumption rate[3] of an individual foodstuff *p* (kg/e),

DF_{ing} is the dose coefficient for ingestion of radionuclide *i* (Sv/Bq),

$C_{p,i}$ is the concentration of radionuclide *i* in foodstuff *p* at the moment of consumption (Bq/kg).

The calculation for $C_{p,i}$ is a function of not only the two discharge methods, atmospheric and surface water, but also is dependent on the radionuclide characteristics as well as the methods of irrigation, uptake from soil, foraging, grazing and bioaccumulation. As such, a separate model for calculating radionuclide concentration is needed for vegetation, meat, milk and fish. The concentration values will be reported in the results section of this report but details of the individual $C_{p,i}$ models can be found in *Section 5* of the IAEA SRS No. 19 manual.

Total Dose:

The total dose of the critical population (Sv/e) for a given radionuclide *i* is finally calculated as the sum of the potential dose pathways given in Equations [4,5,6, and 9]:

$$E_{tot,i} = E_{inh} + E_{im} + E_{gr} + E_{ing,p} \qquad [10]$$

Then the total dose for all radionuclides considered (only ^{137}Cs and ^{90}Sr for this study) is calculated as follows:

$$\sum E_{tot,i} \qquad \text{for all } i \text{ radionuclides} \qquad [11]$$

[3] These rates are differentiated by adult rates and infant consumption rates for vegetation, meat, milk, and fish.

Model Results

A simulated scenario of a catastrophic wildfire event in the Exclusion Zone surrounding Chernobyl would release radioactive materials, including ^{137}Cs and ^{90}Sr, into the population living in the vicinity of the CEZ. **Table 1** shows the estimated quantities of radioactive ^{137}Cs and ^{90}Sr materials in the forest floor and vegetation within the CEZ for the year 2010. The total amount of radioactive material that could potentially be mobilized to an ionized state in the event of a catastrophic wildfire is estimated to be 1.7×10^{15} Bq residing in the forest floor and 1.1×10^{14} Bq in the vegetation. Assuming that a catastrophic wildfire event would completely burn the upper duff layer of the forest floor and the vegetation within a period of five days (4.32×10^{5} s), the average rate of atmospheric discharge of ionized radioactive material was determined to be 4.0×10^{9} Bq/s from the forest floor and 2.5×10^{8} Bq/s from the vegetation. A wildfire scenario would not be responsible for discharging radioactive material directly into surrounding water bodies such as the Kiev Reservoir but the surface water would receive radioactive depositions as the ^{137}Cs and ^{90}Sr settled from the atmospheric plume as either dry or wet deposits. Using Equation 3 for the average discharge rate for a radionuclide assuming no direct discharge into water and data on the surface area of the Kiev Reservoir (9.22×10^{5} m^2), the total surface water discharge for the Kiev Reservoir associated with a catastrophic wildfire from the CEZ was estimated to be approximately 1.8×10^{6} Bq/s for the duration of the fire.

In the event of a catastrophic wildfire the population surrounding the CEZ would be exposed to ionizing radiation by a number of pathways including:

i. Internal exposure from radioactive materials absorbed into the body through inhalation.
ii. Internal exposure from radioactive materials absorbed into the body through immersion during the passage of the radioactive plume.

iii. External exposure to radioactive materials from ground depositions.

iv. Internal exposure from the ingestion of radioactive materials in the form of contaminated vegetation, meat, milk, and fish products.

Before estimates of the effective dose equivalent to the critical population for each pathway could be determined, estimates of the concentrations of ^{137}Cs and ^{90}Sr in the air, water, ground and food products were needed. These concentrations, with the exception of water which was assumed to mix thoroughly for the Kiev Reservoir water body, are a function of distance from the discharge source. As would be expected, when one moves further from the CEZ, the concentrations of radioactive materials in the air, ground and food products decrease. This report considered 10 km rings radiating out from the CEZ starting at 20 km from the source and continuing out to 150 km from the Exclusion Zone (**Figure 1**). The capital of the Ukraine, Kiev, is located approximately 100 km from the CEZ. The estimated concentrations of ^{137}Cs and ^{90}Sr in the air, water, ground and food for distances of 50, 100, and 150 km encircling the CEZ are given in **Table 2**. These values were calculated using Equations 1, 2, & 7 for the air, water and ground concentrations. The equations for calculating food concentrations can be found in *Section 5* of the IAEA SRS No. 19 manual. The highest potential source of radioactive material concentrations at all spatial distances comes from ground concentrations. For example, at the 100 km distance from the CEZ, approximately 4.8×10^{7} Bq/m^{2} of ^{137}Cs and 2.5×10^{7} Bq/m^{2} of ^{90}Sr can be found settling on the ground from wet and dry depositions compared to 10.9 Bq/m^{2} of ^{137}Cs and 5.8 Bq/ m^{2} of ^{90}Sr estimated to be in the atmosphere at 100 km from the CEZ.

Finally, the doses estimated for each pathway of exposure are given in **Table 3.** Again, exposure rates for distances of 50, 100, and 150 km from the CEZ are reported independently for both ^{137}Cs and ^{90}Sr and then total exposures assuming an additive effect for both radionuclides are provided.

Inhalation rates and food consumption patterns are markedly different for adults and infants in the critical population and therefore are estimated separately for this analysis. The exposure from inhalation for adults were based on inhalation rates of 8400 h/a while infant inhalation rates were assumed to be on the order of 1400 h/a (IAEA SRS No. 19 2001). Similarly, the exposure from contaminated foods were based on consumption rates per adults of 410 kg/a for vegetables, 100 kg/a for meat, 250 L/a for milk, and 30 kg/a for fish while infant rates were based on 150 kg/a for vegetables, 40 kg/a for meat, 300 L/a for milk, and 15 kg/a for fish. At a distance of 100 km from the CEZ, the total dose exposure for adults of ^{137}Cs was estimated to be approximately 2.7×10^{-2} Sv/e while the estimate of adult exposure to ^{90}Sr was approximately 5.4×10^{-3} Sv/e.

In summary, the estimated potential effective dose equivalent from radioactive materials volatilized by a catastrophic wildfire in the Exclusion Zone surrounding Chernobyl and transported through the environment to distances equal to and beyond the distance of the capital city Kiev from the source is only two orders of magnitude less than the reported lethal limit of ^{137}Cs and ^{90}Sr in Sieverts per annum according to the International Atomic Energy Agency.

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Figures and Tables

Figure 1: Concentric rings around CEZ

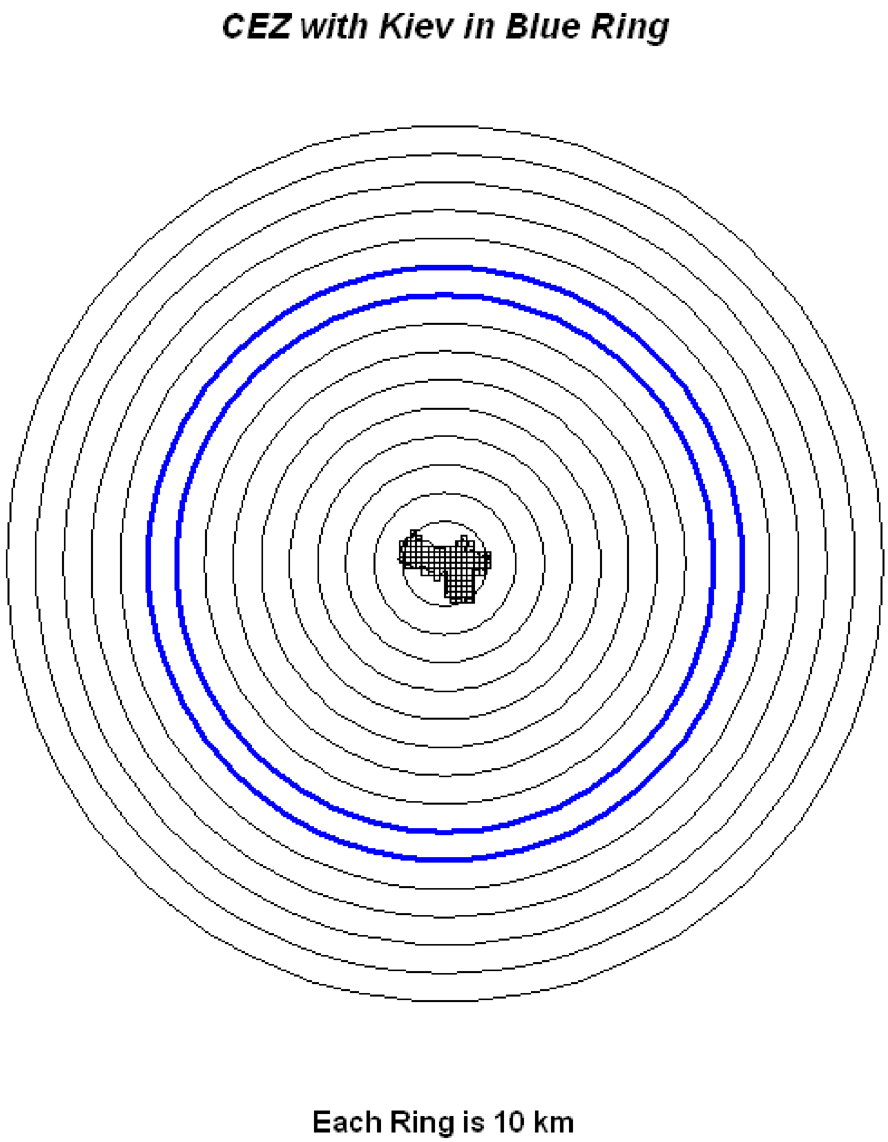

Figure 2: Overview of systems-based approach to modeling the impact of discharges of radioactive substances to the environment (Modified from Figure 2, page 8, IAEA SRS No. 19).

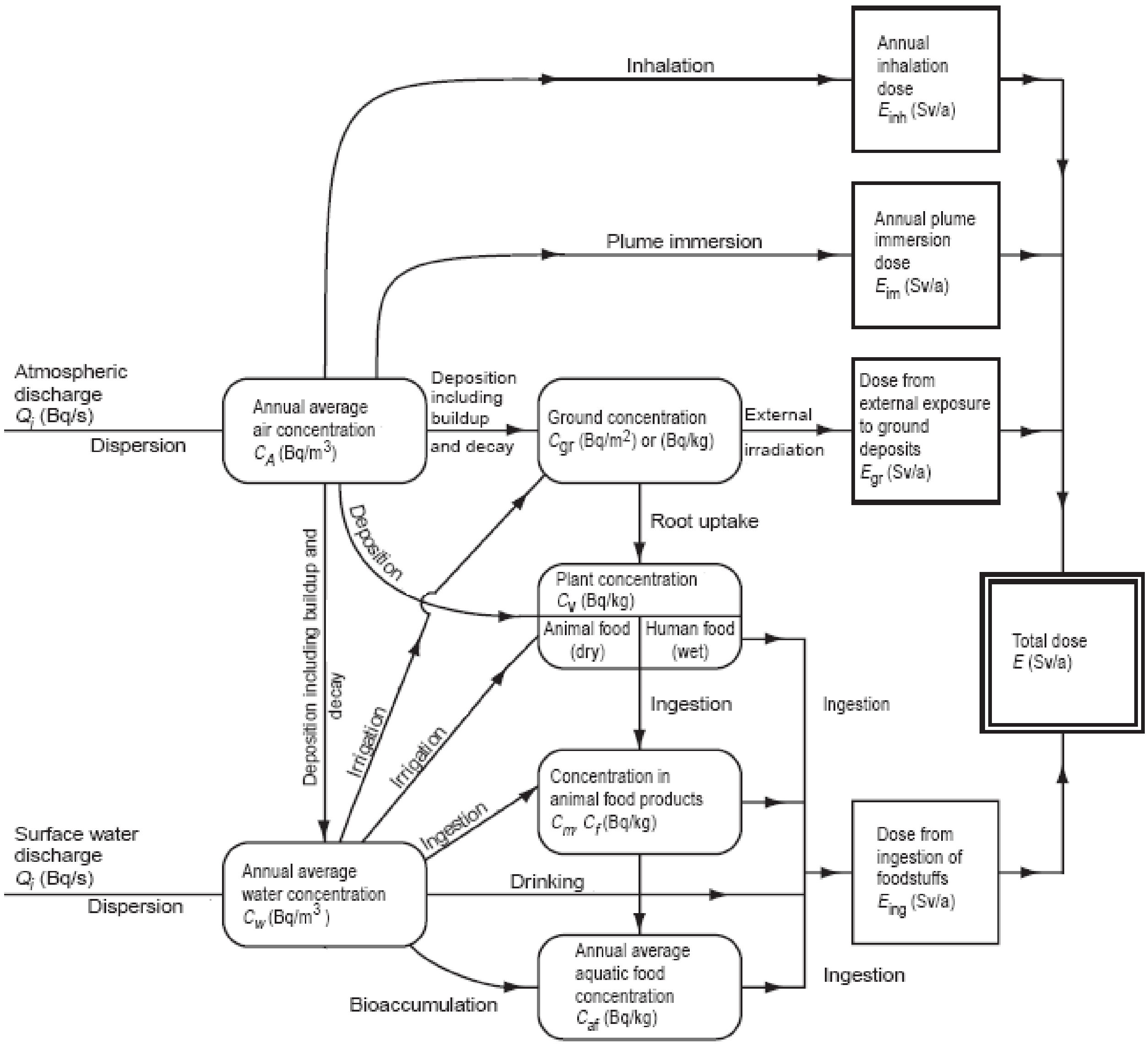

Table 1. Estimated quantities of radioactive materials within the CEZ.

Radionuclides	Estimated Amount (Bq)		Atmospheric Discharge, Q_i (Bq/s)		Surface Water Discharge, Q'_l (Bq/s)
	Forest floor	Vegetation	Forest Floor	Vegetation	
^{137}Cs	1.1×10^{15}	6.8×10^{13}	2.6×10^{9}	1.6×10^{8}	1.2×10^{6}
^{90}Sr	6.1×10^{14}	3.7×10^{13}	1.4×10^{9}	8.5×10^{7}	6.3×10^{5}
Total	**1.7×10^{15}**	**1.1×10^{14}**	**4.0×10^{9}**	**2.5×10^{8}**	**1.8×10^{6}**

Table 2. Estimated concentrations of radioactive materials in the environment after a simulated catastrophic wildfire.

Distance (km)	Radionuclide	Air Concentration C_A (Bq/m^3)	Water Concentration C_W (Bq/m^3)†	Ground Concentration C_{gr} (Bq/m^2)	Food Concentration (Bq/kg)			
					Vegetation	Meat	Milk	Fish†
50	^{137}Cs	30.9	676.6	1.4×10^{8}	1.7×10^{5}	9.6×10^{5}	3.1×10^{5}	4.1×10^{3}
	^{90}Sr	16.5	359.5	7.2×10^{7}	6.3×10^{4}	1.6×10^{5}	9.1×10^{4}	16.2
100	^{137}Cs	10.9	-	4.8×10^{7}	5.9×10^{4}	3.4×10^{5}	1.1×10^{5}	-
	^{90}Sr	5.8	-	2.5×10^{7}	2.2×10^{4}	5.7×10^{4}	3.2×10^{4}	-
150	^{137}Cs	5.9	-	2.6×10^{7}	3.2×10^{4}	1.8×10^{5}	6.0×10^{4}	-
	^{90}Sr	3.2	-	1.4×10^{7}	1.2×10^{4}	3.1×10^{4}	1.7×10^{4}	-

†: These concentration values are reported for the Kiev Reservoir and are therefore not directly associated with distances from the center of the CEZ

Table 3. Estimated effective dose equivalent rates for the critical population.

Distance (km)	Radionuclide	Inhalation E_{inh} (Sv/e) Adults	Inhalation E_{inh} (Sv/e) Infants	Immersion E_{im} (Sv/e)	Ground Exposure E_{gr} (Sv/e)	Ingestion† E_{ing} (Sv/e) Adults	Ingestion† E_{ing} (Sv/e) Infants	Total E (Sv/e) Adults	Total E (Sv/e) Infants
50	^{137}Cs	1.6×10^{-5}	3.2×10^{-6}	3.7×10^{-7}	3.3×10^{-2}	4.3×10^{-2}	2.6×10^{-2}	7.7×10^{-2}	5.9×10^{-2}
	^{90}Sr	3.0×10^{-5}	1.3×10^{-4}	7.0×10^{-10}	3.5×10^{-3}	1.2×10^{-2}	7.1×10^{-3}	1.5×10^{-2}	1.1×10^{-2}
100	^{137}Cs	5.8×10^{-6}	1.1×10^{-6}	1.3×10^{-7}	1.1×10^{-2}	1.5×10^{-2}	9.1×10^{-3}	2.7×10^{-2}	2.1×10^{-2}
	^{90}Sr	1.1×10^{-5}	4.5×10^{-5}	2.5×10^{-10}	1.2×10^{-3}	4.1×10^{-3}	2.5×10^{-3}	5.4×10^{-3}	3.8×10^{-3}
150	^{137}Cs	3.1×10^{-6}	6.1×10^{-7}	7.0×10^{-8}	6.4×10^{-3}	8.3×10^{-3}	5.0×10^{-3}	1.5×10^{-2}	1.1×10^{-2}
	^{90}Sr	5.8×10^{-5}	2.4×10^{-5}	1.3×10^{-10}	6.6×10^{-4}	2.2×10^{-3}	1.4×10^{-3}	2.9×10^{-3}	2.0×10^{-3}

†: These concentration values are reported for the Kiev Reservoir and are therefore not directly associated with distances from the center of the CEZ