Wildfire in the Chernobyl Exclusion Zone: A Worst Case Scenario

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Table of Contents

Tables

ABSTRACT

The potential implications of a catastrophic wildfire in the Ukrainian portion of the Chernobyl Exclusion Zone (CEZ) on populations living and working near the CEZ were assessed. The complete analysis consisted of four linked sub-models: a source model, a transport model, an exposure model, and a cancer risk model. As a worst case scenario, it was assumed that a fire would consume the biomass of pine forests and former agricultural lands and release any associated radionuclides into the atmosphere. The transport model assumed that the wind would blow primarily towards Kiev throughout the fire event. The exposure model was used to estimate exposure through immersion and inhalation during the fire itself and ground exposure in the year following a catastrophic wildfire in the CEZ. The analysis was designed to be extremely conservative and most likely over-estimates potential exposure. The estimated exposure of populations 25 or more kilometers from the source of the fire through these three pathways is below the critical thresholds that would require evacuations. However, Ukrainian law would require limiting ingestion of certain foodstuffs to avoid exposure via ingestion. The cancer risk model assumed that exposure through contaminated foodstuffs would be avoided. If this prohibition were enforced, even a catastrophic wildfire would result in very few additional cancer deaths.

INTRODUCTION

On April 26, 1986, a chain reaction occurred in reactor No. 4 of the Chernobyl nuclear power plant. The resulting explosions released approximately 1.85×10^{18} Becquerel (Bq) of radioactive material into the surrounding environment (Othman, 1990). Residents were permanently evacuated from a 30 km zone around the plant – the Chernobyl exclusion zone (CEZ) – which was determined to have especially high levels of contamination. Radioactive material has been incorporated into both the soil and vegetation. Fires in the CEZ have been both frequent and widespread. From 1992 to 1994, 200 forest fires occurred in the CEZ (Lujaniene et al., 2006). Combustion of organic matter has been shown to lead to resuspension (Kashparov et al., 2000; Yoschenko et al., 2006a; Yoschenko et al., 2006b) and long range transport (Lujaniene et al., 2006) of radionuclides.

The analysis described in this report was designed to assess the potential implications of a catastrophic wildfire consuming pine forests and former agricultural lands in the Ukrainian portion of the CEZ on populations living and working near the exclusion zone. The city of Kiev (population 2.7 million) is located approximately 100 km south east of Chernobyl; Chernigiv (population 305,000) is located approximately 100 km north west of Chernobyl. The report does not directly address the potential exposure of personnel living and working within the CEZ itself. In particular, it does not address the exposure of fire fighters who might be called upon to contain a wildfire. Nor does the report address the consequences of Ukrainian and Belorussian portions of the CEZ burning simultaneously. Analysis of a broader catastrophic forest fire that affected both countries is beyond the scope of this study.

Both the transport and exposure models are designed to be extremely conservative and most likely over-estimate potential exposure. The exposure results are reported as the average *dose* in Sieverts per year (Sv/a) absorbed by a *critical population* during and for the first year after a catastrophic wildfire event in the Chernobyl Exclusion Zone (CEZ). Dose is a measure of energy deposited by radiation within a human target. The critical population consists of the members of the public who 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 exposure pathways. In this report, it is assumed that the average annual dose attributable to a catastrophic wildfire will be highest in the first year after the event. Consequently, exposure for subsequent years is not calculated.

The analysis described in this report was based primarily on a generic screening model for use in assessing the impact of discharges of radioactive substances to the environment (IAEA, 2001). 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 accounts for all major pathways of radiation exposure and is purposefully conservative, reporting risk for cases that involve maximum exposure potential. Transport of the discharged materials is considered through the atmosphere. Exposure pathways for external and internal mechanisms are systematically traced.

Four exposure pathways (ingestion, inhalation, immersion, ground deposition) were modeled for six[1] isotopes (^{90}Sr, ^{137}Cs, ^{154}Eu, ^{238}Pu, ^{239,240}Pu, and ^{241}Am). ^{90}Sr and ^{137}Cs are the two most common radioisotopes in the CEZ and, along with ^{154}Eu, have relatively high dose coefficients for external exposure pathways. Although they are less common, ^{238}Pu, ^{239,240}Pu, and

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[1] Independent estimates for were not available for the stock of ^{239}Pu and ^{240}Pu in the CEZ. The pooled stock of ^{239,240}Pu is treated as a single isotope.

^{241}Am have high dose coefficients for internal exposure pathways (i.e. inhalation and ingestion). 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 exposure pathways. Finally, the additional risk of cancer incidence and cancer mortality attributable to the exposure through inhalation, immersion, and ground deposition were estimated. For reasons explained below, ingestion was not considered in the calculation of cancer incidence and mortality.

METHODS

All models represent abstractions of reality and cannot capture the full complexity of natural systems. Simplifying assumptions must be made both when data is not available and when the dynamics of the system being studied are not fully understood. The model presented here represents a parsimonious abstraction of radionuclide movement through an idealized environment. The relatively small number of model parameters is intended to provide more transparent understanding of the mechanics of radiation dispersion and subsequent exposure. The model can be conceived of as four linked sub-models in which the results from one sub-model are the inputs to the next.

Source model

The stock of radionuclides in combustible material was estimated as a function of the stocks of radionuclides known to be in the soil of the CEZ (Table 1). Kashparov et al. (2003) estimated the total inventory of fuel component radionuclides in the upper 30-cm soil level in the Ukrainian portion of the CEZ (excluding radioactive waste storage sites and cooling ponds) for the six radio-isotopes used in this study. The stock of radionuclides expected to be in the soil in 2010 was estimated as:

$$N_{i,\ 2010} = N_{i,2000}e^{-\lambda_i t} \qquad [1]$$

where

$N_{i,\ 2010}$ is the amount of radionuclide i in the soil in 2010 (Bq),

$N_{i,\ 2000}$ is the amount of radionuclide i in the soil in 2000 (Bq),

λ_i is the decay constant of radionuclide (d^{-1}),

t is the number of days between 2000 and 2010 (d).

No attempt was made to account for losses through processes other than radioactive decay. For the purposes of this report, it was assumed that the radioisotopes were distributed uniformly in the soils of different cover types: former agricultural lands were assumed to have the same average concentration of radioisotopes as pine forests.

Radioisotopes located in the litter layer and in aboveground biomass were assumed to be potentially combustible. Concentration factors were used to estimate stocks of radionuclides in potentially combustible material as a function of soil concentration. Estimates of radionuclide concentrations in soil, vegetation, and litter in two grassland plots and one forest plot in the CEZ for ^{90}Sr, ^{137}Cs, ^{238}Pu, and ^{239,240}Pu (Yoschenko et al. 2006b) were used to estimate concentration factors for those four isotopes in grassland and pine forest. The concentration factor for ^{241}Am was assumed to be twice that for ^{239,240}Pu (Sokolik et al. 2004). The concentration factor for ^{154}Eu was assumed to be equal to that for ^{239,240}Pu (Lux, Kammerer, Ruhm, & Wirth, 1995). It was assumed that the 32% of the CEZ classified as deforested/former agricultural areas and the 38% of the CEZ classified as pine forests could burn. Total stock of radioisotope i in combustible material in 2010 was estimated as:

$$N_{i,comb2010} = \sum_{l=1}^{n} N_{i,2010}\, CF_{i,l} L_l \qquad [2]$$

where

$N_{i,comb2010}$ is the total stock of radioisotope i in combustible material in the CEZ (Bq),

$N_{i,2010}$ is the stock of radioisotope i in the soil in 2010 (Bq),

$CF_{i,l}$ is the concentration factor of isotope i in land class l,

L_l is the proportion of the CEZ in landclass l.

Transport model

The primary means of transporting radioactive material through the environment in the event of a catastrophic wildfire would be atmospheric discharge. The resuspended radioactive material would then be dispersed via a radioactive plume and finally be deposited on ground and water surfaces.

Resuspension

It was assumed that all vegetation and litter in both pine forests and former agricultural land in the Ukrainian portion of the CEZ would burn over a five day period.[2] Thus, the total discharge of isotope i to the atmosphere was assumed to be $N_{i,comb2010}$. The rate of atmospheric discharge (Qi), measured in Bq/s, was calculated as the total amount of the isotope for the year 2010 divided by the time period of the wildfire event (sec).

The atmospheric discharge was treated as a point source[3] and its trajectory was modeled using a Gaussian plume model. The wind was assumed to blow towards Kiev at 2 m/s for 90% of

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[2] Assuming complete combustion of all potentially combustible products in both forest and agricultural lands is extremely conservative and is unlikely to occur in reality. First, fires tend to be patchy and do not consume all vegetation or litter in their path. Second, tree trunks, which contain a large proportion of combustible ^{90}Sr and a smaller proportion of the combustible ^{137}Cs, are unlikely to be completely consumed by even the most intense crowning fires. Finally, the entire CEZ is unlikely to burn completely in any one year. However, assuming complete combustion is consistent with a worst case scenario.

[3] While this is a simplifying assumption, it is appropriate for our purposes: developing a worst case scenario model. A point source model treats the full stock of radioisotopes as if it is concentrated in a single place. Thus, it should overestimate air concentration both above that point and along the path of the plume.

the duration of the wildfire. Dispersion, or the average air concentration during the event (CA) measured at a given distance from the source, was calculated as:

$$C_A = \frac{P_p F Q_i}{u_a} \qquad [3]$$

where

C_A is the ground level air concentration at downwind distance *x* in sector *p* (Bq/m^3)[4],

P_p is the fraction of time per event that the wind blows toward the target population,

F is the Gaussian diffusion factor[5] appropriate for a given release height[6] and downwind distance *x* (m^{-2}),

Qi is the average discharge rate per event for radionuclide i (Bq/s),

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

Ground concentration

For this model, it was assumed that the ground surface was represented by an infinite plane upon which all radionuclide deposition activity was uniformly distributed. The infinite plane model for estimating the dose from ground deposition was chosen because of the limited

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[4] As formulated in the IAEA model, C_A at a given distance is independent of deposition velocity. Thus, the model does not take into account depletion of the plume due to deposition to the ground.

[5] The Gaussian diffusion factor formula is given on page 18 of the IAEA SRS No. 19. It assumes a neutral atmospheric stability class (Pasquill–Gifford stability class D).

[6] Emission height was assumed to be 0 m. This gives the highest possible ground level air concentration (and hence, highest level of contamination). In an actual cataclysmic fire one would expect the emission height to be 10s to 100s of meters. This would have the effect of spreading the contamination over a larger area and making the effects in any one location less serious. Thus, assuming a release height of 0 m is conservative.

duration of the wildfire event for downward migration of radionuclides.[7] Ground concentration at a distance x from the source of emission was calculated as:

$$C_{gr} = \frac{d_i\left[1 - e^{-\lambda_{E_i^s} t_b}\right]}{\lambda_{E_i^s}} \qquad [4]$$

where

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

t_b is the duration of the wildfire (d),

$\lambda_{E_i^s}$ 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:

$$d_i = (V_d)C_A \qquad [5]$$

where

V_d is the deposition coefficient (deposition velocity[8]) for a given radionuclide *i* (1000 m/d),

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

Water concentration

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[7] For extremely long lived radionuclides or for terrain that is highly variable, a method to track migration through a soil column should be considered. A number of theoretical models exist that attempt to predict this downward movement but there is very little empirical data to validate these predictions.

[8] As recommended in IAEA (2001) deposition velocity was assumed to be 1000 m/d. The model assumes that deposition velocity does not vary with distance. In an experimental forest fire in the CEZ Yoschenko et al. (2006) found that total deposition velocity was high near the fire because of the rapid settling of large particles (e.g., partially burned pieces of organic mater). At distances of several hundred meters, deposition velocity was less than 1000 m/d. It is likely that 1000 m/d overestimates the deposition velocity one would encounter in a real fire.

A catastrophic wildfire could potentially increase the level of radioactivity in water bodies adjacent to or flowing out of the CEZ. Deposition could contaminate the water bodies directly. Enhanced erosion from burned areas could indirectly introduce contaminated sediments to the water bodies. However, the water bodies most likely to be affected (e.g., Kiev Reservoir, Pripyat River) are used neither for irrigation nor as a source of municipal drinking water (Kashparov, personal communication). Consequently, this analysis assumes that contaminated water would not be a major exposure pathway.

Exposure model

Once the discharge and dispersion mechanisms are modeled, the potential pathways for critical population exposure can be modeled. The exposure pathways chosen for this model included: inhalation, plume immersion, exposure to surface deposits and ingestion of foodstuffs. Exposures via inhalation and plume immersion are assumed to be transient: They cease to be factors after the plume has passed. Exposures via surface deposits and ingestion are assumed to occur for the full year following the wildfire.

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. The dose coefficients assume a 50 year life expectancy for adults and a 70 year life expectancy for infants. The model assumes that both groups will be exposed to the ambient air concentration for the full duration of the wildfire event and that ambient air concentration will return to normal immediately following the event.

The effective dose from inhalation for both adults and infants after exposure to radionuclide transportation from a catastrophic wildfire in the CEZ was calculated as:

$$E_{inh} = C_A R_{inh} DF_{inh} \qquad [9]$$

where

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

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

R_{inh} is the inhalation rate during the wildfire event (m^3/a),

DF_{inh} is the inhalation dose coefficient (Table 2; Sv/Bq).

For adults, R_{inh} is 115 m^3/a or $\frac{8400\ m^3/a}{365\ d/a} * 5\ d$. For infants, R_{inh} is 19 m^3/a or $\frac{1400\ m^3/a}{365\ d/a} * 5\ d$.

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. This implies 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. However, in order to ensure that the critical population represents the highest risk group possible, the instantiation of the model presented here did not incorporate the effect of buildings. As with inhalation, the model assumes that both groups will be exposed to the ambient air concentration for the full duration of the wildfire event and that ambient air concentration will return to normal immediately following the event. In practice, most individuals will not remain exposed to the plume cloud for the duration of the wildfire event.

The effective dose from immersion in the atmospheric plume is calculated as:

$$E_{im} = C_A DF_{im} O_f \qquad [10]$$

where

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

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 (Table 2; Sv/a per Bq/m),

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

Surface exposure:

The radioactive material deposited to the ground was assumed to linger for the entire year. Individuals were assumed to be exposed to surface deposits for the entire year. In practice, individuals may be exposed to a lower level during the time they spend indoors or outside of the region contaminated by the plume. Isotope specific effective dose coefficients are reported in Table 2.

The effective dose from ground deposition was calculated as follows:

$$E_{gr} = C_{gr} DF_{gr} O_f \qquad [11]$$

where

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

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

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

Cgr is the deposition density of radionuclide *i* (Bq/m^2), obtained from Equation [3].

Ingestion

The food chain models assume that the critical population is exposed to radionuclides through ingestion of crops, meat, and milk products that have been exposed to atmospheric discharges. Much like the rates of atmospheric inhalation, the ingestion of vegetation, meat, and milk is highly variable within a population; however conservative estimates of normal consumption rates for adults and children are available (Table 3). The general calculation of the periodic effective dose from consumption of radionuclide *i* in foodstuff *p* is:

$$E_{ing,p} = C_{p,i} H_p DF_{ing} \qquad [12]$$

where

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

H_p is the consumption rate[9] 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 Cp,i is a function of discharge method, radionuclide characteristics, methods of cultivation, irrigation, foraging, and grazing. As such, a separate model for calculating radionuclide concentration is needed for vegetation, meat, and milk. The models are outlined here. Details of the individual Cp,i models can be found in *Section 5* of IAEA SRS No. 19.

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 incorporated into vegetation through foliar absorption or root

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[9] Rates for crops, meat, and milk are differentiated by adult rates and infant consumption rates for vegetation, meat, and milk.

uptake. Radioactive decay, growth dilution, non-contaminated water wash-off, and soil fixation can eventually lead to reductions in the radionuclide concentration within vegetation. The model estimates the exposure that would occur over the course of the year following the wildfire if one were to eat only crops grown on soil contaminated as the radioactive plume passed by.[10] Element-specific transfer factors were used which take into account both uptake from soil and soil adhesion to the surface of plants (Table 4).

The intake of radionuclides by animals depends on the size, species, age, feed material, and milk yield. Element-specific transfer factors were used to account for the transfer from feed to milk and meat products (Table 4). For this study, it was assumed that the meat from animals originated as cattle byproducts and that the cattle grazed on pasture with soil contaminated by the plume during the grazing season. The concentration of radionuclides in the milk was dependant upon the radioactivity concentration in the feed consumed by the milk-producing animals. This study used values specific to dairy cows; however, the values are also applicable to other lactating animals without significantly underestimating the radioactive concentration in those milk products.

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]:

$$E_{tot,i} = E_{inh} + E_{im} + E_{gr} + E_{ing,p} \qquad [13]$$

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[10] Vegetation directly exposed to deposition from the plume was assumed not to be consumed. Consuming crops exposed to direct deposition could lead to a higher dose than is reported here. However, it seemed extremely unlikely that an individual would consume only plants directly exposed to the radioactive plume. Urban dwellers are unlikely to consume food produce only from those farms that happened to be in the path of the plume. Furthermore, exposed surfaces of vegetation would gradually be washed with rainwater. Exposure to this pathway might be minimal if the fire happened subsequent to harvest or prior to planting. It might also mitigated through government intervention to destroy or temporarily quarantine crops directly exposed to the plume.

Then the total dose for all radionuclides considered is calculated as follows:

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

Cancer incidence and mortality model

The risk of developing cancer and the risk of dying from cancer as a result of exposure through inhalation, cloud emersion, and ground exposure were estimated. For these calculations, it was assumed that highly contaminated food would not be consumed. Lifetime attributable risk of cancer incidence and cancer mortality was modeled as a function of age at time of exposure, sex, and dosage. The estimated number of additional cancer cases per 100,000 population exposed to 0.1 Sv was reported by the Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation (2006; Table 5)[11]. The Committee's preferred model assumes a linear relationship of risk between the actual exposure and the calculated exposure values. Thus, additional cancer incidence can be calculated as:

$$M_{D,a,s} = \frac{LAR_{a,s}}{0.1/D} \qquad [11]$$

where,

$M_{D,a,s}$ is the additional risk of mortality per 100,000 people of a given sex (s) who are a given age (a) at the time of exposure to an expected dose (D).

$LAR_{a,s}$ is the Lifetime attributable risk for 100,000 people of a given sex (s) who are a given age (a) at the time of exposure to a one time dose of .1 Sv, and

D is the expected dose.

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[11] The BEIR VII estimates were obtained as combined estimates based on relative and absolute risk transport and, strictly speaking, are applicable to U.S. populations rather than Ukrainian populations.

RESULTS

A catastrophic wildfire event in the Exclusion Zone surrounding Chernobyl would release radioactive materials into the population living in the vicinity of the CEZ. Table 1 shows the estimated quantities of radioactive materials in potentially combustible materials within the Ukrainian portion of 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 2.1×10^{14} Bq in the vegetation and forest floor litter layer. Assuming that a catastrophic wildfire event would occur over a period of five days (4.32×10^{5} s), the average rate of atmospheric discharge of ionized radioactive material was determined to be 4.9×10^{8} Bq/s.

Estimates of the concentrations of each radioisotope in the air, ground, and food products as a function of distance from the discharge source are reported for distances of 25, 50, 100 and 150 km from the discharge source (Table). The values at 25 km are within the CEZ itself. As would be expected, when one moves farther from the CEZ, the concentrations of radioactive materials in the air, ground, and food products decrease. The concentration that would be incorporated into food crops from the soil over the course of a growing season is several orders of magnitude lower than the concentration of radioactivity on crop surfaces attributable to direct deposition immediately after the wildfire event (Table 7). In this study, it was assumed that crops and forage exposed directly to the plume would not be consumed.

The doses estimated for each pathway of exposure are given in Table 8. Again, exposure rates for distances of 25, 50, 100, and 150 km from the center of the CEZ are reported for individual isotopes and then total exposures assuming an additive effect for all isotopes are provided. The primary contributors to exposure are (in order) ^{90}Sr, ^{137}Cs, ^{241}Am and ^{239,240}Pu. The highest dose for immersion is provided by ^{137}Cs. The highest dose for the other three pathways is provided by ^{90}Sr. Ingestion is the single most important source of exposure. ^{239,240}Pu and ^{241}Am are important to both inhalation and ingestion. At 100 km, the adult exposure though pathways other than ingestion during the first year after the event is 4.7x10^{-4} Sv/a (0.47 mSv/a). Ingestion is responsible for an additional Sv/a 1.7x10^{-3} Sv/a (1.7 mSv/a) during that first year. For infants, the equivalent figures are 3.3x10^{-4} Sv/a (0.33 mSv/a) and Sv/a 3.0x10^{-3} Sv/a (30 mSv/a).

The additional risk of cancer incidence and mortality for males and females exposed through pathways other than ingestion at distances of 25, 50, 100 and 150 km are given in Table 9. If we assume that infants would not be permitted inside of the CEZ itself, the highest calculated risk is to 20 year old women residing at 25 km from the center of the CEZ. Their additional lifetime risk of dying from cancer would be 29 per 100,000. The additional lifetime risk of dying of cancer for 20 year old men residing at 25 km from the center of the CEZ would be 19 per 100, 000.

DISCUSION

The model that forms the basis for the estimates presented here (IAEA 2001) is a screening model. It is intended to run without a lot of site specific data. Instead, the parameter values given in the IAEA report are intentionally very conservative and the model is designed to over-estimate the dosage that is likely to be received. If the estimated dosages still fall below the level of concern, one can conclude that the actual dosages will be below the level of concern. On the other hand, if the estimated dosages are greater than the level of concern, then a more refined model may be needed to determine whether actual dosages are likely to exceed an acceptable level.

According to the United Nations Scientific Committee on the Effects of Atomic Radiation, the worldwide average background dose is 2.4 mSv/a (UNSCEAR, 2000). According to the same report, a single chest CT has an average effective dose of 5-20 mSv (depending on country); a chest x-ray has an effective dose of 0.007-0.017 mSv. Occupational dose limits have been set at 100 mSv in five years or an annual average of 20 mSv/a (Radiological & Protection Publication 60, 1990). The limiting dose for the general public has been set at 1mSv/a.

The Ukrainian government has developed safety norms to govern the level of intervention as a function of the prevented dose. Populations should be evacuated if the prevented dose in the first two weeks exceeds 50 mSv. Time spent outdoors should be limited if the prevented dose in the first two weeks exceeds 1 mSv for children and 2 mSv for adults. Resettlement should occur if the prevented dose for the first 12 months exceeds 50 mSv; if the prevented dose during the resettlement exceeds 200 mSv; or if the terrestrial density of the contamination exceeds 400 kBq/m^2 for ^{137}Cs, 80 kBq/m^2 for ^{90}Sr, or 0.5 kBq/m^2 for $^{238\text{-}240}$Pu and ^{241}Am. Temporary resettlement could occur if the average prevented dose exceeds 100 mSv or if the average monthly dose for the resettlement period exceeds 5 mSv per person

The combined estimated dosages from cloud immersion during the fire itself, inhalation during the fire itself, and ground exposure in the year subsequent to the fire for adults are 2.4 mSv/a, 1.3 mSv/a, 0.47mSv/a, and 0.26 mSv/a at 25, 50, 100, and 150 km from the center of the CEZ (calculated from Table 8). For infants, the equivalent estimates are 1.7 mSv/a, 0.93 mSv/a, 0.33 mSv year, and 0.18 mSv/a. These exposure levels represent worst case scenario values for the critical population based on very conservative assumptions. Values for adults at 25 and 50 km and for children at 25 km exceed the dosage limits set by in Radiological & Protection Publication 60 for the general public. However, even at 25 km, the estimated dose does not rise to the level that precautions such as resettlement or limiting the time spent outdoors would be called for[12]. Even if dosages were underestimated by an order of magnitude, they would be less than the level deemed acceptable for occupational exposure.

On the other hand, the potential dosage derived from the consumption of contaminated foodstuffs could exceed acceptable levels. The Ukrainian government calls for limitations on the consumption of foodstuff if the prevented internal irradiation dose exceeds 5 mSv or if the prevented average annual dose exceeds 1 mSv. For both adults and infants these levels could be almost met or exceeded by consuming food produced at distances as great as 150 km from the center of the CEZ. Limitations on the consumption of milk is called for if the radioactive contamination by ^{137}Cs exceeds 100 Bq/l or if the contamination by ^{90}Sr exceeds 20 Bq/l for adults or 5 Bq/l for children. The limits for other foodstuffs are 200 Bq/kg for ^{137}Cs and 40 Bq/kg (adults) or 10 Bq/kg (children) for ^{90}Sr. Both milk and meat produced on land directly along the trace of the plume could exceed the acceptable level of ^{90}Sr at distances as great as 150 km (Table 7). Crops produced at 50 km exceed the acceptable level of ^{90}Sr. Thus, consumption of these foodstuffs would be banned by the government.

It is important to note, however, that the highest levels of contamination would occur directly along the trace of the plume. As one moved away from the trace, contamination levels would decline. Consequently, the actual amount of agricultural land that would need to be taken out of production would be limited.

While it was beyond a scope of this study to develop a detailed epidemiological model[13], it is possible to estimate roughly the extent of possible health consequences of a fire. From an

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[12] The exposure is calculated for a point directly along the trace of the plume. Approximately half of this dose is attributable to ground exposure over the course of the year following the wildfire. Exposure could be mitigated by reducing the time spent in this location over the course of the year. Alternatively voluntarily limiting time spent outdoors during the actual fire event could also reduce exposure but would not be required under Ukrainian law.

epidemiological standpoint, the worst case scenario would be if the trace of the plume intersected with a major population center, such as Kiev. If we assume:

1) the entire population of Kiev (2.7 million) was exposed to the trace;

2) the population had a sex ratio of 1:1 at the time of the fire; and

3) the average age of the population was 20 at the time of the fire; and

4) residents successfully avoided exposure through ingestion;

then we would expect 168 additional cancers[14] to be diagnosed over the lifetime of the residents based on the exposure during the first year after the fire. We would expect 81 additional cancer deaths to occur.

While statistics on lifetime risks of cancer incidence and mortality in Ukraine were not available to us and calculating these values is beyond the scope of this paper, the number of additional cancer deaths can be put into context by comparing them to current (non-age adjusted) mortality rates in Ukraine. According to statistics compiled by the World Health Organization Mortality Database (WHO, 2005), in 2005 the total death rate and cancer death rate for Ukrainian females was 1469.5 per 100,000 and 158.8 per 100,000, respectively. For males the rate equivalent rates were 1862.2 per 100,000 and 238.8 per 100,000. Thus, 11% of deaths among females and 13% of deaths among males were attributable to cancer. If we do not take age effects into account, one would expect 11-13,000 deaths from cancer per 100,000 deaths. Given these background rates of cancer mortality, the additional cancers would not be distinguishable from normal occurrences.

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[13] A more refined assessment would require, among other things, taking into account the demographic structure and geographic distribution of the population around the CEZ, modeling the plum in three dimensions rather than two, developing a model to take into account transport of the deposited radionuclides through the soil over time, and estimating the amount of exposure likely to occur through ingestion despite efforts limiting consumption of highly contaminated food.

[14] (0.78 occurrences per 1,000,000 women + 0.46 occurrences per 1,000,000 men)/2*2.7 million=168

CONCLUSION

A catastrophic wildfire in the Ukrainian portion of the CEZ which completely consumed the vegetation and litter in former agricultural lands and pine forests could release approximately 2.1×10^{14} Bq of radioactive material. A screening model using conservative assumptions was used to estimate exposure through immersion and inhalation during the fire itself and ground exposure in the year following the fire. The estimated exposure of populations 25 or more kilometers from the source of the fire through these three pathways is below the critical thresholds that would require evacuations. However, Ukrainian law would require limiting ingestion of certain foodstuffs to avoid exposure via ingestion. Estimating the likely exposure to people living and working within the exclusion zone was beyond the scope of this study, but could exceed the critical thresholds.

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Table 1. Estimated fuel component radionuclides in soil and vegetation of the 30-km Chernobyl exclusion zone in Ukraine in 2000 and 2010. Fuel component radionuclides in 2000 in upper 30-cm soil layer outside the ChNPP industrial site, excluding the activity located in the radioactive waste storages and in the cooling pond are from Kashparov et al. (2003). Estimates of concentration factors (ratio of radionuclides in vegetation and litter to soil) in forest and grasslands were derived from Lux et al. (1995), Sokolik et al. (2004), Yoschenko et al. (2006).

Radionuclide	Radionuclide Inventory (Bq)			Ratio Combustible/Soil	
	Soil in 2000	Soil in 2010	Combustible in 2010	Forest	Grassland
^{90}Sr	7.7E+14	6.1E+14	1.5E+14	0.351	0.023
^{137}Cs	2.8E+15	2.2E+15	5.8E+13	0.101	0.037
^{154}Eu	1.4E+13	6.4E+12	8.5E+10	0.031	0.005
^{238}Pu	7.2E+12	6.7E+12	8.4E+10	0.03	0.004
^{239,240}Pu	1.5E+13	1.5E+13	2.0E+11	0.031	0.005
^{241}Am	1.8E+13	1.8E+13	4.7E+11	0.062	0.01

Table 2. Effective immersion, surface, inhalation, and ingestion dose coefficients for various radioisotopes (IAEA 2001).

Radionuclide	Immersion (Sv/a per Bq/m^3)	Surface (Sv/a per Bq/m^2)	Inhalation (Sv/a per Bq/m^3)		Ingestion (Sv/a per Bq/kg)	
			Adult	Infant	Adult	Infant
^{90}Sr	3.1E-09	3.5E-09	1.6E-07	4.0E-07	2.8E-08	7.3E-08
^{137}Cs	8.7E-07	1.8E-08	4.6E-09	5.4E-09	1.3E-08	1.2E-08
^{154}Eu	2.0E-06	3.8E-08	5.3E-08	1.5E-07	2.0E-09	1.2E-08
^{238}Pu	1.7E-10	2.9E-11	4.6E-05	7.4E-05	2.3E-07	4.0E-07
^{239,240}Pu	1.6E-10	2.8E-11	5.0E-05	7.7E-05	2.5E-07	4.2E-07
^{241}Am	2.6E-08	8.9E-10	4.2E-05	6.9E-05	2.0E-07	3.7E-07

Table 3. Ingestion of food stuffs per year (IAEA 2001).

	Intake per person	
Ingestion	Adult	Infant
Fruit, vegetables and grain (kg/a)	410	150
Milk (L/a)	250	300
Meat (kg/a)	100	40

Table 4. Element specific transfer factors for terrestrial foods for screening purposes (IAEA 2001).

Element	Forage (Bq/ kg plant dry weight)/ (Bq/kg soil dry weight)	Crops (Bq/ kg plant fresh weight)/ (Bq/kg soil dry weight)	Milk (d/L)	Meat (d/kg)
Sr	10	0.3	0.003	0.01
Cs	1	0.04	0.01	0.05
Eu	0.1	2.0E-03	6.0E-05	2.0E-03
Pu	0.1	1.0E-03	3.0E-06	2.0E-04
Am	0.1	2.0E-03	2.0E-05	1.0E-04

Table 5. Lifetime attributable risk of cancer incidence and cancer mortality per 100,000 people exposed to a single dose of 0.1 Sv (Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, 2006).

Age at time of exposure	Incidence (occurrences/ 100,000 people)		Mortality (occurrences/100,000 people)	
	Female	Male	Female	Male
0	4777	2563	1770	1099
20	1646	977	762	511
40	886	648	507	377
60	586	489	409	319
80	214	174	190	153

Table 6. Estimated concentrations of radioactive materials in the environment after a catastrophic wildfire.

Radionuclide	Distance (km)	Air Concentration (Bq/m^3)	Ground Concentration (Bq/m^2)	Food Concentration (Bq/kg)		
				Vegetation	Meat	Milk
^{90}Sr	25	39	2.0E+05	230	1800	720
	50	14	6.9E+04	79	630	250
	100	4.8	2.4E+04	28	220	89
	150	2.6	1.3E+04	15	120	49
^{37}Cs	25	15	7.6E+04	12	350	93
	50	5.3	2.7E+04	4.1	120	33
	100	1.9	9.4E+03	1.4	43	12
	150	1	5.1E+03	0.78	23	6.3
^{154}Eu	25	2.2E-03	110	8.6-04	2.1E-02	8.3E-05
	50	7.9E-03	39	3.0E-04	7.2E-04	2.9E-05
	100	2.8E-03	14	1.1E-04	2.5E-04	1.0E-05
	150	1.5E-03	7.5	5.8E-05	1.4E-04	5.6E-06
^{238}Pu	25	2.2E-02	110	4.3E-04	2.0E-04	4.1E-06
	50	7.8E-03	39	1.5E-04	7.2E-05	1.4E-06
	100	2.7E-03	14	5.3E-05	2.5E-05	5.1E-07
	150	1.5E-03	7.5	2.9E-05	1.4E-05	2.8E-07
^{239,240}Pu	25	5.3E-02	260	1.0E-03	4.9E-04	9.7E-06
	50	1.9E-02	93	3.6E-04	1.7E-04	3.4E-06
	100	6.5E-03	33	1.3E-04	6.0E-05	1.2E-06
	150	3.5E-03	18	6.8E-05	3.3E-05	6.5E-07
^{241}Am	25	1.2E-01	620	4.8E-03	2.0	5.3E-01
	50	4.4E-02	220	1.7E-03	7.0E-01	1.9E-01
	100	1.5E-02	77	5.9E-04	2.5E-01	6.5E-02
	150	8.4E-03	42	3.2E-04	1.3E-01	3.6E-02

Table 7. Estimated concentration of radioactive material in crops. Deposition is the concentration on plant surfaces estimated immediately after a catastrophic wildfire. Soil uptake and adhesion is estimated for the growing season immediately following a catastrophic wildfire.

		Crop Contamination (Bq/kg)	
Radionuclide	Distance	Deposition	Soil Uptake and Adhesion
^{90}Sr	25	52000	230
	50	18000	79
	100	6400	28
	150	3500	15
^{137}Cs	25	20000	12
	50	7000	4.1
	100	2500	1.4
	150	1400	0.78
^{154}Eu	25	30	8.6E-04
	50	10	3.0E-04
	100	3.7	1.1E-04
	150	2	5.8E-05
^{238}Pu	25	29	4.3E-04
	50	10	1.5E-04
	100	3.6	5.3E-05
	150	2	2.9E-05
^{239,240}Pu	25	70	1.0E-03
	50	25	3.6E-04
	100	8.7	1.3E-04
	150	4.7	6.8E-05
^{241}Am	25	170	4.8E-03
	50	58	1.7E-03
	100	20	5.9E-04
	150	11	3.2E-04

Table 8. Estimated effective dose for the critical population after a catastrophic wildfire.

Radionuclide	Distance (km)	Immersion (Sv/a)	Ground.Exposure (Sv/a)	Inhalation (Sv/a)		Ingestion (Sv/a)		Total (Sv/a)	
				Adult	Infant	Adult	Infant	Adult	Infant
^{90}Sr	25	1.7E-09	6.8E-04	7.2E-04	3.0E-04	1.3E-02	2.4E-02	1.4E-02	2.5E-02
	50	5.8E-10	2.4E-04	2.5E-04	1.1E-04	4.5E-03	8.3E-03	5.0E-03	8.6E-03
	100	2.1E-10	8.5E-05	8.9E-05	3.7E-05	1.6E-03	2.9E-03	1.7E-03	3.0E-03
	150	1.1E-10	4.6E-05	4.9E-05	2.0E-05	8.5E-04	1.6E-03	9.5E-04	1.7E-03
^{137}Cs	25	1.8E-07	1.4E-03	8.0E-06	1.6E-06	8.2E-04	5.2E-04	2.2E-03	1.9E-03
	50	6.3E-08	4.8E-04	2.8E-06	5.5E-07	2.9E-04	1.8E-04	7.7E-04	6.6E-04
	100	2.2E-08	1.7E-04	9.9E-07	1.9E-07	1.0E-04	6.5E-05	2.7E-04	2.3E-04
	150	1.2E-08	9.2E-05	5.4E-07	1.1E-07	5.5E-05	3.5E-05	1.5E-04	1.3E-04
^{154}Eu	25	6.1E-10	4.2E-06	1.4E-07	6.4E-08	1.2E-09	2.8E-09	4.4E-06	4.3E-06
	50	2.2E-10	1.5E-06	4.8E-08	2.3E-08	4.1E-10	9.9E-10	1.5E-06	1.5E-06
	100	7.6E-11	5.3E-07	1.7E-08	8.0E-09	1.4E-10	3.5E-10	5.4E-07	5.3E-07
	150	4.1E-11	2.9E-07	9.2E-09	4.3E-09	7.8E-11	1.9E-10	3.0E-07	2.9E-07
^{238}Pu	25	5.2E-14	3.2E-09	1.2E-04	3.1E-05	4.5E-08	2.9E-08	1.2E-04	3.1E-05
	50	1.8E-14	1.1E-09	4.1E-05	1.1E-05	1.6E-08	1.0E-08	4.1E-05	1.1E-05
	100	6.4E-15	4.0E-10	1.5E-05	3.9E-06	5.6E-09	3.6E-09	1.5E-05	3.9E-06
	150	3.5E-15	2.2E-10	7.9E-06	2.1E-06	3.0E-09	2.0E-09	7.9E-06	2.1E-06
^{239,240}Pu	25	1.2E-13	7.4E-09	3.0E-04	7.8E-05	1.2E-07	7.3E-08	3.0E-04	7.8E-05
	50	4.1E-14	2.6E-09	1.1E-04	2.7E-05	4.1E-08	2.6E-08	1.1E-04	2.7E-05
	100	1.4E-14	9.1E-10	3.8E-05	9.6E-06	1.4E-08	9.1E-09	3.8E-05	9.6E-06
	150	7.8E-15	5.0E-10	2.0E-05	5.2E-06	7.9E-09	4.9E-09	2.0E-05	5.2E-06
^{241}Am	25	4.4E-11	5.5E-07	6.0E-04	1.6E-04	6.6E-05	8.8E-05	6.7E-04	2.5E-04
	50	1.6E-11	1.9E-07	2.1E-04	5.8E-05	2.3E-05	3.1E-05	2.3E-04	8.9E-05
	100	5.5E-12	6.9E-08	7.4E-05	2.0E-05	8.2E-06	1.1E-05	8.3E-05	3.1E-05
	150	3.0E-12	3.7E-08	4.0E-05	1.1E-05	4.5E-06	5.9E-06	4.5E-05	1.7E-05
Total	25	1.8E-07	2.1E-03	1.7E-03	5.7E-04	1.4E-02	2.5E-02	1.7E-02	2.7E-02

50	6.4E-08	7.2E-04	6.1E-04	2.1E-04	4.8E-03	8.5E-03	6.2E-03	9.4E-03
100	2.2E-08	2.6E-04	2.2E-04	7.1E-05	1.7E-03	3.0E-03	2.1E-03	3.3E-03
150	1.2E-08	1.4E-04	1.2E-04	3.8E-05	9.1E-04	1.6E-03	1.2E-03	1.9E-03

Table 9. Lifetime attributable risk of cancer incidence and mortality per 100,000 people for various levels of exposure.

Distance (km)	Dose (mSv)	Age at time of exposure	Incidence (occurrences/100,000 people)		Mortality (occurrences/100,000 people)	
			Female	male	female	male
25	2.7	0	127.6	68.4	47.3	29.3
	3.8	20	62.6	37.1	29.0	19.4
	3.8	40	33.7	24.6	19.3	14.3
	3.8	60	22.3	18.6	15.5	12.1
	3.8	80	8.1	6.6	7.2	5.8
50	0.9	0	44.4	23.8	16.4	10.2
	1.3	20	22.0	13.1	10.2	6.8
	1.3	40	11.8	8.7	6.8	5.0
	1.3	60	7.8	6.5	5.5	4.3
	1.3	80	2.9	2.3	2.5	2.0
100	0.33	0	15.6	8.4	5.8	3.6
	0.47	20	7.8	4.6	3.6	2.4
	0.47	40	4.2	3.1	2.4	1.8
	0.47	60	2.8	2.3	1.9	1.5
	0.47	80	1.0	0.8	0.9	0.7
150	0.18	0	8.4	4.5	3.1	1.9
	0.26	20	4.2	2.5	1.9	1.3
	0.26	40	2.3	1.7	1.3	1.0
	0.26	60	1.5	1.2	1.0	0.8
	0.26	80	0.5	0.4	0.5	0.4

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