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Potential Dose to Firefighters from Inhalation of Radionuclides in Smoke

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Summary

Fires in regions with radiological contamination result in radiological doses to emergency responders. Estimating fuel conditions and modeling hypothetical smoke dispersion determined that regulatory dose limits were not exceeded in most cases. Modeling plume rise further reduced the likelihood of receiving unsafe doses. This methodology can be applied to most burn scenarios to estimate potential dose received.

Abstract

Firefighters and emergency personnel responding to fires in areas where the surface litter and live vegetation contains radiological contamination will receive a radiological dose by inhaling re-suspended radioactive material contained in the smoke. Using published data on radionuclide activities in wildland fuels, we modeled hypothetical radionuclide emissions, downwind dispersion exposure and dose at the Savannah River Site for 70th and 97th percentile environmental conditions and for average and high fuel loads. The volatilization of radionuclides was estimated from the temperature of vaporization of the various elements using analogous volatilization data from vegetation nutrients. We predicted downwind concentration and potential dose to personnel along the flank and near the fire front for radionuclides of interest (^{137}Cs, ^{238}Pu, ^{90}Sr and ^{210}Po). Predicted concentrations exceeded dose guidelines in the base case scenario for ^{238}Pu at 70th percentile environmental conditions and average fuel load for both 4 and 14 hour shifts. Under 97th percentile environmental conditions and high fuel loads, dose guidelines were exceeded for several reported cases for radionuclides of ^{90}Sr, ^{238}Pu, and ^{210}Po. The potential for exceeding regulatory limits was mitigated by including plume rise (> 2 m s^{-1}) and moving a small distance from the fire flank or front as the concentration gradients were large near the edge of the fire. This approach can be applied to other cases and provides a method for quickly estimating dose levels of airborne radionuclides in wildland fire environments.

INTRODUCTION

Wildland firefighters and emergency response personnel will receive a radiation dose through inhalation when exposed to radionuclides emitted during forest wildfires and prescribed fires. Natural isotopes of radon (^{222}Rn) decay, beryllium (^{7}Be) and potassium (^{40}K) exist in significant amounts in forest wildland fuels (LeCloarec et al. 1995, Sugihara et al. 1997, Hejl et al. 2013). However, background levels from natural sources, and those from aboveground atomic weapons testing prior to the Strategic Arms Limitation Treaty, are not thought to be a health concern when compared to fine particulate matter ($PM_{2.5}$) (Volkerding 2003, Paatero et al. 2009, Commodore et al. 2012). In contrast, wildland fuels contaminated by nuclear incidents are of great concern (Pazukhin et al. 2004, Hao et al. 2009). Unless acceptable risk levels in fuels are established for emergency response personnel, they may be unwilling to contain wildfires or reduce hazardous fuels by prescribed burning, which will increase risk to the public. The radionuclides of greatest concern are isotopes that are present due to aerial transport and deposition and are re-cycled by vegetation. These include radioisotopes of cesium (^{134,137}Cs), plutonium (^{238}Pu), uranium (^{235,238}Ur), strontium (^{90}Sr), polonium (^{210}Po) and thorium (^{232}Th). The most common contaminate is usually ^{137}Cs; it was released in large quantities during atmospheric weapons testing and it remains in the environment for relatively long periods of time (Paller et al. 2014).

Emission factors for particulates, ozone and many organic compounds are related to combustion efficiency and type of fuel (Andreae and Merlet 2001, Akagi et al. 2011). Only emissions factors associated with natural levels of ^{210}Po in wildland fuels have been estimated (LeCloarec et al. 1995, Reinhardt et al. 2004). A major challenge with radionuclides is determining dose when the activity of the radionuclides in wildland fuels can range from background levels to amounts many orders of magnitude above background levels following a nuclear incident (Yoschenko et al 2006, Hashimoto et al. 2012). These limitations can be avoided if elements and their isotopes have an estimable fraction loss (*FL*) as the fuel is consumed (Eq. 1):

$$E = m \cdot FL_i \cdot A \qquad (1)$$

where E is the average rate of radionuclide emission (Bq ha^{-1} hr^{-1}) during a fire, m is the rate of fuel mass consumed (kg ha^{-1} hr^{-1}), and A is the amount of isotope i in the fuel (Bq kg^{-1}) . If the radionuclide activity, amount of available fuel and rate of fuel consumption can be estimated, then only a method to estimate FL for the 'i^{th}' fuel consumption condition for radionuclides of concern is required. The emissions can then be tied to fire spread and input into an appropriate dispersion model to determine exposure and dose under various environmental conditions and fire control strategies.

Our objective is to: 1) provide a general method to make radionuclide emission estimates; 2) couple emissions to fire spread, fuel consumption and smoke dispersion; and 3) estimate firefighter exposure and dose under most likely and upper range scenarios from worldwide case studies of radionuclide activities in fuels. Our approach attempts to capture the dominant processes affecting dose and to facilitate assessment of a range of radionuclides and their activities (Fig. 1). We use the Savannah River Site (SRS) as a model landscape for this analysis. We compare the potential firefighter doses to a commonly used administrative guideline level of 0.25 milliSievert (mSv), which is $1/4^{th}$ the annual dose limit of 1 milliSievert (mSv) for members of the public and non-radiological workers in the United States.

Methods

The SRS is located in the southeastern U.S. and it is a large (~800 km^2) U.S. Department of Energy (DOE) nuclear facility that also has been designated as a National Environmental Research Park. About 90% of SRS land area consists of natural and managed forests which are maintained by the U. S. Department of Agriculture Forest Service – Savannah River. The managed pine forest was used as a model system for the dose estimates. The weather conditions, range of available fuel, fire behavior, smoke emissions and firefighter tasks are typical of many southeastern U.S. forests. The environmental and forest conditions are well characterized (Kilgo and Blake 2005). Selected radionuclides in wildland fuels and smoke have been reported (Commodore et al. 2013, Hejl et al. 2013).

Fraction Loss of Forest Nutrients

Since studies on FL for radionuclides are rare, the fire emission chemistry of major elements in vegetation is a reasonable analogue (Boerner 1982). Following a large number of studies, Raison et al (1985) proposed that the FL of many elements in native fuels during wildland fires is related to the temperature of vaporization (TOV) of the element and the degree to which the fuel is combusted. Elements with low TOV like nitrogen (N) had a FL of 97% under almost complete combustion due to the predominance of the vaporization process at wildland fuel flaming combustion temperatures (600 to 800^{o}C). In contrast, calcium (Ca) has a high TOV and its FL was lower under similar conditions (11%). The TOVs for the vegetation elements and radionuclides range from -200^{o}C to about 4800^{o}C (Table 1). Based upon Raison et al. (1985) work, we established an upper boundary for FL for N at 97% (see Fig. 1a in Raison et al. (1985)). They determined Ca was conserved during fires and an estimated upper boundary (FL_{ub}) value of 11% was used (see Fig. 2 and 3 in Raison et al. (1985)). These FL_{ub} values represent emissions from surface litter, partially decayed organic material, leaves, small twigs and branch fuels that typically support surface fires. These two points allowed us to establish an upper boundary as a simple relationship between FL_{ub} versus TOV. A constant FL of 11% for elements between Ca and Th was set as an upper boundary for all elements with TOV greater than Ca.

Under varying environmental conditions that affect fuel moisture and the fire spread rate, the rate of fuel consumption and hence the actual FL_i for the 'ith' condition will generally be less than the FL_{ub}. Raison et al (1985) have shown that the FL_i for elements as a function of the proportion of the fuel consumed generally follows a linear relationship with approximately constant slope and zero intercept depending upon the experimental conditions (field, laboratory, etc.). Therefore, the expected FL_i for N when the proportion of the fuel consumed is less than 100% is the FL_{ub} (0.97) multiplied by the fuel consumption fraction. The corresponding FL_i for Ca, as well as all other elements with TOV greater than Ca, is FL_{ub} (0.11) multiplied by the fuel consumption fraction. The actual FL_i can be then be approximated by:

$$FL_i = FL_{ub} * F_C / F_L \quad (2)$$

where F_C is the amount of fuel consumed (kg ha^{-1}) and F_L is the total fuel load (kg ha^{-1}). Observations of FL of other vegetation elements with TOV ≤ TOV_{Ca} were compiled from studies by Raison et al. (1985), Grier (1975), Christensen (1977), Amiro et al. (1996) and Niemeyer et al. (2005) to evaluate the upper boundary assumption and the negative trend between decreasing FL and TOV. The FL of ^{137}Cs for surface dead fuels (for the litter, duff, and fine woody) from a Canadian forest and for ^{210}Po in savanna grassland fires in Africa was also determined (LeCloarec et al. 1995, Paliouris et al. 1995). Finally, the FL from laboratory studies of Si, Fe, Mn and Cu from Evans and Allen (1971) were included. These elements are all minor vegetation elements with TOV > TOV_{Ca}.

Radionuclide Activity in Fuels

Data to represent radionuclide activity in modeled fuels are obtained from published literature for both background and contaminated cases. The contaminated fuel measurements are taken from reported activities in forest fuels at Chernobyl and Fukushima (Yoschenko et al. 2006, Hashimoto et al. 2012). Background radionuclide levels, including some long distance fallout, were obtained from SRS pine forests, African savannas, Japanese forests, Canada boreal conifer forests and deciduous Irish forests (LeCloarec et al. 1995, Paliouris et al. 1995, Seymour et al. 1999, Sugihara et al. 2003, Hejl et al. 2013) (Table 2). Radionuclides are not uniformly distributed in wildland fuel components such as litter, duff, branches, bark wood, live foliage, etc. (Paliouris et al. 1995, Yoschenko et al. 2006). However, there is insufficient information to reliably allocate the various radionuclides among fuel components and then to assign them separate fuel consumption values. We modeled the radionuclide activities as uniformly distributed in a simple composite fine dead fuel (litter, duff, 1 and 10 hour moisture lag woody fuels) for the purposes of estimating potential emissions.

Fuel Consumption and Fire Spread

Fire weather records maintained by the US Forest Service at the SRS were used to model most likely (70^{th} percentile), and upper range (97^{th} percentile) environmental conditions during a fire (Table 3). We used the average (50%) and high (upper 95% confidence interval) levels of fuel loads for loblolly pine forests at the SRS (Parresol et al. 2012). We simulated the initial rate of spread and area for the first hour for each condition by using a head fire and a long needle pine (TL8) fuel model in BehavePlus software (Andrews et al. 2005). All fires were then modeled on a uniform 2-D surface using a version of FARSITE under the70^{th} and 97^{th} environmental conditions and the average and high fuel load until the fire reached about 400 ha (Finney 2004). The latter area has a wildfire return interval of about 14-15 years in the southeastern U.S. (Malamud et al. 2005). The modeled landscape has zero slope and uniform fuel distribution.

Fuel consumption rates for fires as a function of consumption were calculated using the Fire Emission Production Simulator (Anderson et al. 2004). The model simulates total emissions in response to the estimated rate of spread. The modeled fuel consumption is similar to empirically measured results under similar environmental and fuel load condition at the SRS (Goodrick et al. 2010). For the 70^{th} and 97^{th} percentile environmental conditions, the fuel consumption averaged 71% and 85% respectively. These values were then applied to obtain the FL of the various radionuclides of concern.

Radionuclide Emissions and Dispersion

To simplify comparison of a wide range of scenarios we created a scaling approach to compare results to a base case for radionuclide activity, FL, and fuel load. We established that almost all background activities of individual radionuclides are less than 1000 Bq kg^{-1} (Table 2) and created a base case using the 70^{th} percentile condition, average fuel load, and a FL of 1.0. Predicted concentrations and doses for each scenario could then be quickly obtained by scaling our base case concentration and dose predictions by

$$S = \frac{C_s}{C_b} \quad (3)$$

where S is a dimensionless scaling factor and C_s and C_b are the concentrations of a radionuclide of interest in the desired scenario and in the base case scenario, respectively. For the base case, radionuclide activity in the fuel was set to 1092.5 Bq kg^{-1} leading to an emission rate of 1 x 10^7 Bq ha^{-1}. By taking the scaling approach the exposure and dose scenarios of interest can be predicted simply by knowing the concentration of volatized radionuclides and scaling by the base case emission rate (Fig. 2).

The PUFF-PLUME model used for this study is a Gaussian dispersion model that was validated at SRS for radiological emissions and found to give good agreement with measured values (Garrett and Murphy 1981). The model was modified to incorporate multiple sources and used to estimate downwind dispersion of radiological contaminates based on the rate of radionuclide emission. PUFF-PLUME uses the traditional Gaussian dispersion equation to predicted downwind concentrations:

$$X(x,y,z) = \frac{Q}{2\pi U \sigma_y \sigma_z}\left(e^{\frac{-y^2}{2\sigma_y}}\right)\left(e^{\frac{-(z-H(x))^2}{2\sigma_z}}\right)\left(e^{\frac{-(z+H(x))^2}{2\sigma_z}}\right) \quad (4)$$

where $X(x,y,z)$ is the atmospheric concentration in (Bq m^{-3}) at a certain distance downwind (x; m), crosswind distance from the plume centerline (y; m) and elevation (z; m). Q is the source term (Bq), U is the wind speed in (m s^{-1}), σ_y and σ_z are the turbulent diffusion terms and H is the source height (m). Wind speeds were determined by the characterization of the most-likely and upper-range environmental conditions. The turbulent diffusion terms were calculated using guidance from the Environmental Protection Agency (U.S. Environmental Protection Agency 2000) and assuming an extremely unstable environment. The effective source height ($H(x)$; m) changed with downwind distance due to simulated plume rise. The initial source height (H_o) was assumed to be initially at 2 m and increased with downwind distance according to

$$H(x) = H_o w_{rise} \frac{x}{U} \quad (5)$$

where w_{rise} is the rate of plume rise (m s^{-1}).

The basic model assumes no strong turbulent vertical mixing or plume dominated smoke column that would generally be expectedfrom the heat of combustion. To approximate plume rise and its effects on downwind radionuclide concentration, we evaluated vertical lift rates from 1 to 5 m sec^{-1} (Achtemeier 2005). Deposition processes were not modeled due to uncertainties in the dry deposition parameters and to ensure conservatism in the model predicionts. The geometric mean particle size distribution of the Puff-Plume model that is used to simulate radionuclide transport from facilities is within the range of 2.5 micron particulate values for smoke aerosols (Garrett and Murphy 1981).

The model was run at hourly intervals with a new fire front configuration specified for each hour. The fire front was simulated as an elliptical arc stretching to approximately 45 degrees on either side of the wind direction. Sources were placed at 3 m intervals along the arc and the source strength was determined using the fire's rate of consumption. The release rate (R; Bq·m^{-1}·hr^{-1}) was determined by

$$R = \frac{CA}{d} \quad (6)$$

using the number of hectares consumed during the hour (C; ha hr^{-1}) and the estimated radionuclide activity per ha provided by FEPS (A; Bq ha^{-1}) to give a total released activity during the hour. The total activity was then spread evenly across the distance of the arc (d; m) during the modeled hour. Downwind concentrations were predicted in the atmosphere from zero to several hundred meters downwind of the expanding fire ellipse.

Radionuclide Exposure and Dose

Firefighter exposure is related to the concentration of radionuclides in air at the work location and the length of time they work. Exposure occurred downwind within a hypothetical control area either tangential to the fire boundary between 45 and 22.5 degrees between 10 to 50 m downwind of the fire front or within a rectangular zone at 100 m perpendicular to the fire front (Fig. 3). These exposure scenarios reflect a traditional control strategy of anchor, flank and pinch. This geometry allowed dose to be constrained within an order of magnitude range of radionuclide densities in air given the uncertainty in actual exposure. Since the concentration in air varies with the dynamic meteorological conditions and the rate of fire spread, firefighter exposure to radionuclides in air is the mean hourly value over the shift.

The dose received is then a function of the breathing rate and the specific radionuclide(s) inhalation dose coefficient for an adult worker (U.S. Environmental Protection Agency 1988). We set the maximum exposure time as a full 14 hour shift along the fire line. Because wildland firefighters typically shift physical locations or perform fire line duties more rapidly to minimize exposure to smoke, we estimated a typical scenario of 4.0 hours net exposure during a shift (Adetona et al. 2011). A moderate breathing rate of 1.3 m^3 h^{-1} for an industrial worker was assumed. A guideline dose level of 0.25 mSv, which is $1/4^{th}$ the annual DOE dose limit of 1 mSv for members of the public and non-radiological workers was used in the assessment (Fig. 4). Potential dose boundary limits in terms of the order of magnitude dose for each case study were constructed for individual radionuclides reflecting the exposure time, range of activity in emissions at flank and pinch locations, and most likely and upper range conditions.

Results and Discussion

Based on work by Raison et al. (1985), FL estimates were calculated for radionuclides with TOV < TOV_{Ca} (Table 4). Measurement of nutrient losses from selected studies involving wildland fires or fuels generally supports the upper boundary and the decline in FL as the TOV increases (Fig. 4). There is substantial variability below the upper boundary for individual elements. However, because comparable fuel consumption measurements or ancillary variables were not always available, further analysis was limited. The observed FL of ^{210}Po from the one study for which data is available suggests that values may

exceed the estimate derived from the FL vs. TOV relationship. The FL values of 5-17% from Evans and Allen (1971) for vegetation micro-nutrients (i.e. Fe, Mn, Si, Cu) with TOV > TOV_{Ca} were all similar. The FL values range above (+6%) and below (-6%) the expected values of 11% with the highest combustion temperatures associated with the highest FL (17%).

The magnitude of the potential FL of ^{137}Cs, ^{210}Po and ^{90}Sr and their greater sensitivity to fuel consumption relative to other radionuclide contaminates with high TOVs is evident. The concept that the volatility of radionuclide metals is an important factor in fire emissions has been generally accepted principle for several decades (e.g. Amiro et al. 1996). The model we constructed extends this concept by integration of common vegetation nutrients in order to establish a functional relationship between the FL and the TOV. Although most of the observations were obtained under conditions typical of wildland surface fires, the temperature of combustion was rarely known. It can result in much greater FL values if temperatures exceed 800-900^{o}C (Evans and Allen 1971, Amiro et al. 1996). Studies of elemental enrichment in particulate matter during combustion generally follow the proposed relationship between FL and TOV. Aerosol particulates of Mg, K and Cl were enriched by ~1.5x, ~3x and ~15x, respectively (Andreae and Merlet, 2001). The relative relationship of FL to the TOV is also supported by laboratory studies in which a high mass fraction of elements K, CL, and Na were found in particulate emissions relative to Ca, Mg, and Si (Hosseini et al. 2013).

The paucity of data on minor vegetation nutrient elements with TOV > TOV_{CA} and the absence of any data for radionuclides makes the assumption that these elements are conserved during fires worth additional research. Outliers exist in the nutrient studies of Raison et al. (1985) (boron and manganese). Exposure from radionuclides like ^{238}Pu, ^{232}Th and $^{235,238}U$ in wildland fuels is reduced substantially as a result of the low FL. Unfortunately, there are insufficient data to confirm the FL value, although Yoschenko et al. (2006) suggest from their data that emissions of ^{238}Pu during a prescribed fire were substantially lower as a result of its' conservation in ash. In the case of ^{210}Po, the high FL may results from the fact that a high proportion of material exists as aerial deposition on fuel surfaces and not bound

to organic material within in tissues. If surface deposits are more volatile, the FL of natural radionuclides like ^{7}Be and recent fallout materials will be underestimated.

Based on available worldwide data on ^{137}Cs activity in fuels and using average fuel load conditions at SRS, the range of emissions from single radionuclides can range over four orders of magnitude (Fig. 2). Unfortunately, there is very limited data worldwide on either natural or contaminated radionuclide activities in wildland fuels. There are even fewer observations in which a suite of background and contaminate radionuclides have been measured at the same location (Table 2). As a consequence, it is difficult to establish threshold activities of various radionuclides in contaminated fuels adjusted for natural background radionuclides present in the environment. Our dose estimates assume that natural and fallout background levels of other radionuclides contribute relatively little to the overall firefighter dose. For radionuclides with low energy particles and corresponding low dose coefficients, this assumption may be reasonable. For radionuclides with high energy particles and corresponding high dose coefficients such as ^{210}Po, this assumption may not be valid (Fig. 4).

The modeled rate of radionuclide emissions was a consequence of the rate of fire spread, which varied throughout the burn period (Fig. 6). As emissions increased firefighter exposure increased. Exposure was influenced by atmospheric dispersion such that the maximum exposure in the "flank" and "pinch" zones varied by an order of magnitude throughout the burn period. The "flank" position has a steep gradient in radionuclide activity corresponding to dispersion perpendicular to the axis of the plume, whereas the pinch point does not have a steep gradient. Not unexpectedly, the rate of emissions and the dispersion of smoke have a very large impact on firefighter dose for a given shift length. Small changes in the angle of attack and distance to the edge of the fire line can be sufficient to reduce predicted exposure activities by at least an order of magnitude. The maximum predicted concentrations in PUFF-PLUME occurred in the flank region for all scenarios, and typically occurred when the flank angle was low and at close distance to the edge of the fire front, putting fire personnel nearer the center of the plume.

For the radionuclide activities and conditions examined in this study, predicted dose exceeded safe limits during a 4 or 14 hour shift when environmental conditions were unfavorable (97th percentile conditions) and when fuel loading was high (Table 5). The one exception was the hypothetical base case for ^{238}Pu. For ^{137}Cs, which has a high TOV, only one scenario resulted in predicted concentration leading to a dose which exceeded the 0.25 mSv guideline. This case represented the higher activities measured in forest fuels in Fukushima, Japan (Hashimoto et al. 2012). The safe threshold dose was also exceeded under high fuel loads and 97th percentile environmental conditions for activity levels of ^{90}Sr and ^{238}Pu in forest fuels at Chernobyl (Yoschenko et al. 2006). Because we did not attempt to model conditions at either location, these results cannot infer that actual firefighter dose is unsafe at either Chernobyl or Fukushima. The one natural background radionuclide we modeled, ^{210}Po, may be of concern because of its high volitalization potential or FL, and high dose coefficient. ^{210}Po exists worldwide as a result of atmospheric deposition follow a sequence of decay from spillation. Although the half-life is only 138 days, it is produced continuously.

. Our initial modeled scenarios were conservative in that no plume rise was considered despite the known behavior that fire plumes typically exhibit. This approach was applied because descriptions of how quickly plumes rise depend on other environmental conditions and can vary from one fire to another. However, the thermal buoyancy generated by the heat given off from a burn will most likely result in a substantial rate of plume rise, lowering the expected concentration. The potential change in downwind concentration at the flank and pinch regions for a plume rise ranging from 1-5 m s^{-1} for each of the four scenarios resulted in a substantial change in maximum exposure (Fig. 7). The effects of plume rise were more dependent on the environmental conditions and varied little between the cases of average or high fuel loading. For 70th percentile environmental conditions, little change occurred when using a rate of plume rise of 1 m s^{-1}, while a 2 m s^{-1} rate of plume rise was sufficient to reduce the predicted concentration by an order of magnitude. A 3-5 m s^{-1} plume rize reduce maximum activity in air by 3 to 5 orders of magnitude. In the 97th percentile environmental conditions, a 3 m s^{-1} rate of plume rise was necessary to achieve a one order of magnitude reduction in predicted concentration. Given that the 97th

percentile environmental conditions will result in higher emission rates, these conditions appear to partially offset the plume rise effect, but a plume rise of 3-5 m s^{-1} is sufficient to reduce the exposure firefighters receive to a level below the 0.25 mSv level simply based on the order of magnitude effects.

Inhalation dose estimates depend upon the absorption or retention of radionuclides in lung tissue. In our model, we assigned the entire emissions to very fine particulates to maximize dose. In reality, we do not understand how radionuclide chemical complexes are distributed among particle fractions or how quickly aerosol condensation of vaporized radionuclides occurs. If the amount of condensation and concentration in ash or particulates is large, the dose will be proportionally reduced. Dose would also be reduced if we accounted for deposition of emitted material on downwind surfaces. The amount of downwind deposition has been shown through empirical studies to be significant for both nutrient and radionuclide elements (Lewis 1974, LoCloarec et al. 1995, Yoeshencko et al. 2006).

Conclusions

Although firefighters will receive a radiological dose from emissions during a wildfire or prescribed fire, it appears unlikely that the does will not exceed the 0.25mSv standard for a single event except in extreme cases associated with high fuel loads, consumption rates, radionuclide concentrations and volatilization losses in available fuels coupled with poor dispersion and a high dose coefficient. We did not analyze cumulative dose from multiple radionuclides (either background natural elements or contaminate radionuclides from incident releases). The paucity of data currently limits the dose estimates from multiple radionuclides, but may be a significant factor for assessing total dose especially for natural background elements with high dose coefficients. Each of the variables we analyzed can play an important role under the specified fire conditions including the dose coefficients, shift length, attack positions, the volatilization loss of the radionuclide, fuel and environmental conditions. The effects of these variables can be characterized by our modelling, assisting a fire manager's ability to mitigate dose to firefighters through controlling shift time, control positions and avoiding poor atmospheric dispersion conditions.

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Table 1: Vaporization temperature of selected nutrients and radionuclides in whole degrees centigade. Values obtained from the Handbook of Chemistry and Physics (2013)

Selected Nutrients	TOV (^{o}C)
Nitrogen (N)	-196
Chloride (Cl)	-35
Iodine	184
Phosphorus (P)	280
Sulfur (S)	445
Potassium (K)	774
Sodium (Na)	883
Magnesium (Mg)	1107
Calcium (Ca)	1484
Silicon (Si)	2355
Radionuclides	
Cesium (Cs)	768
Polonium (Po)	962
Strontium (Sr)	1384
Bismuth (Bi)	1560
Radium (Ra)	1737
Uranium (Ur)	3818
Plutonium (Pu)	3235
Thorium (Th)	4790

Table 2: Studies and selected radionuclide activities (Bq kg^{-1}) in surface fuels used to model composite fuel radiological emissions, exposure and dose to firefighters.

Case	Fuel	^{137}Cs	^{90}Sr	^{238}Pu	$^{239/240}Pu$	^{40}K	^{226}Ra	^{212}Bi	^{238}U	^{210}Po	^{238}Th
1	Litter	$1..0x10^{1}$	-	-	-	$2.4x10^{1}$	$2.0x10^{2}$	$7.8x10^{1}$	$2.6x10^{2}$	-	$3.8x10^{2}$
2	Peat	$2.4x10^{2}$	-	-	-	-	-	-	-	-	-
3	Humus	$3.6x10^{2}$	-	-	-	$1.6x10^{2}$	-	-	-	-	-
4	Litter	$2.4x10^{4}$	-	-	-	-	-	-	-	-	-
5	Litter	$6.4x10^{4}$	$8.1x10^{4}$	$1.3x10^{2}$	$2.8x10^{2}$	-	-	-	-	-	-
6	Litter	$3.2x10^{5}$	-	-	-	-	-	-	-	-	-
7	Grass	-	-	-	-	-	-	-	-	$8.1x10^{1}$	-
8	Litter	-	-	-	-	-	-	-	-	$7.6x10^{3}$	-

1, Hejl et al. 2013; 2, Paliouris et al. 1995; 3, Seymour et al. 1999; 4, (evergreen forest) Hashimoto et al 2012; 5, Yoschenko et al. 2006; 6, (deciduous forest) Hashimoto et al 2012; 7, LeCloarec et al. 1995; 8, Sugihara et al. 1997.

Table 3: Fuel and environmental inputs to the Fire Emission Production Simulator and FARSITE models to establish "most likely" and "upper range" emission estimates.

	Most Likely	**Upper Range**
Fuel Component	Fuel Loading (Mg ha^{-1})	
Litter	5.8	10.5
Duff	8.8	21.3
Woody	2.62	6.2
Shrub/Vines	0.4	1.0
Grasses/Forbs	0.2	0.6
Total	17.8	39.6
	Fuel Initial Moisture Content (%)	
Percentile Range	70^{th}	97^{th}
Litter (1h)	6	4
Duff (partially decayed)	100	50
Litter (10h)	8	7
Live foliage	90	60
	Range of Atmospheric Conditions	
Relative Humidity (%)	34-47	19-45
Temperature (^{o}C)	26-29	27-36
Wind Speed (m s^{-1})	0.9-2.2	0.9-4.5

Table 4: Estimates of the fraction loss for various radionuclides with temperatures of volatilization less than calcium. Values correspond to the upper boundary (100% fuel consumption) (FL_{ub} = 86.976 – 0.0512 (TOV)); the 70th percentile (71% fuel consumption) (FL_{70} = 57.404 - 0.0338 (TOV)); and the 97th percentile (85% fuel consumption) (FL_{97} = 73.919 - 0.0436 (TOV)) environmental conditions.

Radionuclide	FL_{70}	FL_{97}	FL_{ub}
^{129}I	0.551	0.659	0.777
^{40}K	0.337	0.402	0.473
^{137}Cs	0.339	0.404	0.476
^{210}Po	0.268	0.320	0.377
^{90}Sr	0.115	0.136	0.161

Table 5: Estimated maximum single radionuclide dose to firefighters in flanking positions under most likely and upper range fuel and environmental conditions. Most likely conditions are 70th percentile environmental conditions and average fuel loading. Upper-range conditions are 97th percentile environmental conditions and high fuel loading. Exposures are listed for a 4-hour and a14-hour shift. Radionuclide activities and case numbers correspond to Table 2. Dose levels that exceed the 0.25 mSv threshold level are in bold.

Case Study	Most Likely		Upper Range		Fuel Radionuclide (activity Bq kg^{-1})
	4h shift	14h shift	4h shift	14h shift	
Base	$4.04 \cdot 10^{-5}$	$1.41 \cdot 10^{-4}$	$1.82 \cdot 10^{-3}$	$6.38 \cdot 10^{-3}$	^{137}Cs (1092.5)
1	$1.25 \cdot 10^{-7}$	$4.37 \cdot 10^{-7}$	$6.73 \cdot 10^{-6}$	$2.36 \cdot 10^{-5}$	^{137}Cs
2	$3.01 \cdot 10^{-5}$	$1.05 \cdot 10^{-5}$	$1.62 \cdot 10^{-4}$	$5.67 \cdot 10^{-4}$	^{137}Cs
5	$4.51 \cdot 10^{-5}$	$1.57 \cdot 10^{-5}$	$2.42 \cdot 10^{-4}$	$8.49 \cdot 10^{-4}$	^{137}Cs
7	$3.01 \cdot 10^{-4}$	$1.05 \cdot 10^{-3}$	$1.62 \cdot 10^{-2}$	$5.66 \cdot 10^{-2}$	^{137}Cs
8	$4.01 \cdot 10^{-3}$	$1.40 \cdot 10^{-2}$	0.22	**0.76**	^{137}Cs
9	$8.02 \cdot 10^{-4}$	$2.80 \cdot 10^{-3}$	$4.31 \cdot 10^{-2}$	0.15	^{137}Cs
Base	$1.64 \cdot 10^{-3}$	$5.75 \cdot 10^{-3}$	$7.41 \cdot 10^{-2}$	**0.26**	^{90}Sr (1092.5)
9	$1.40 \cdot 10^{-2}$	$4.90 \cdot 10^{-2}$	**0.747**	**2.61**	^{90}Sr
Base	**0.45**	**1.74**	**22.3**	**0.78**	^{238}Pu, $^{239/240}$Pu (1092.5)
9	$9.92 \cdot 10^{-3}$	$3.48 \cdot 10^{-2}$	**0.54**	**1.89**	^{238}Pu, $^{239/240}$Pu
Base	$1.19 \cdot 10^{-2}$	$4.16 \cdot 10^{-2}$	**0.54**	**1.88**	^{210}Po (1092.5)
3	$2.36 \cdot 10^{-3}$	$8.27 \cdot 10^{-3}$	0.13	**0.45**	^{210}Po
4	$2.22 \cdot 10^{-2}$	$7.75 \cdot 10^{-2}$	**1.19**	**4.18**	^{210}Po

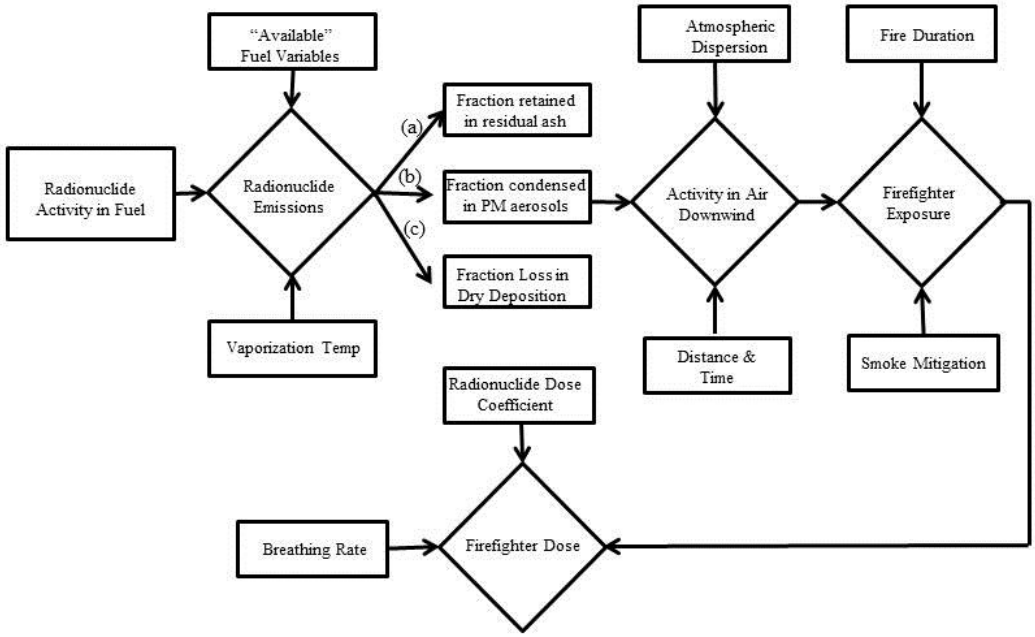

Figure 1: Dominant processes controlling dose to firefighters from radionuclides in smoke.

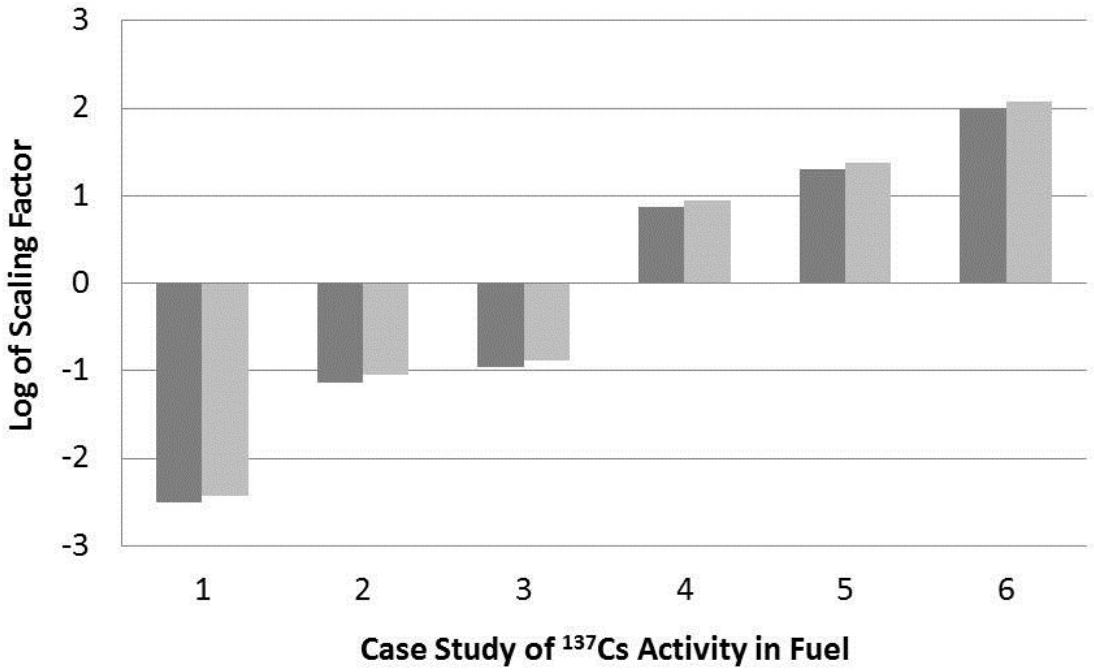

Figure 2: Emissions scaling factors for ^{137}Cs under mostly likely and upper range environmental and fuel load conditions. The base case is 1 x 10^{7} Bq ha^{-1} 70^{th} percentile environmental conditions, average fuel load, a fraction loss of 1 and a hypothetical activity of 1092.5 Bq kg^{-1}. The case study numbers correspond to Table 2.

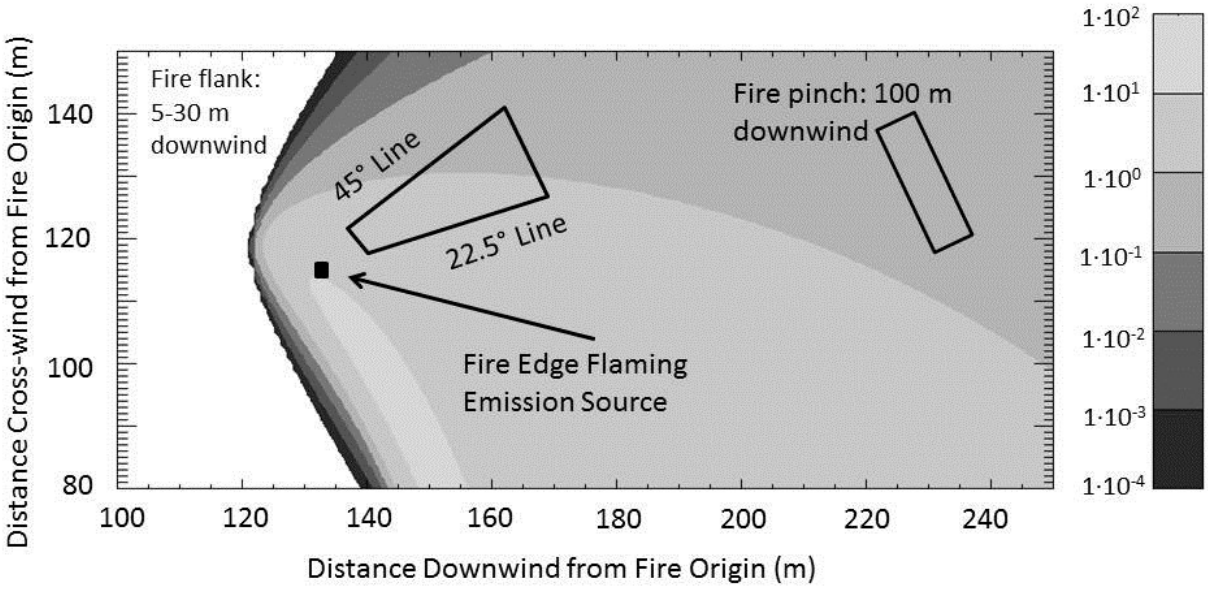

Figure 3: An example of modeled concentration downwind of a fire front using the base-case simulation. The outlined areas represent the flank position (near the Edge Source), which is expected to be between 10-40 m away from the fire along a line 22.5° and 45° off the plume transport direction, and the pinch zone, estimated to be 100 m ahead of the fire.

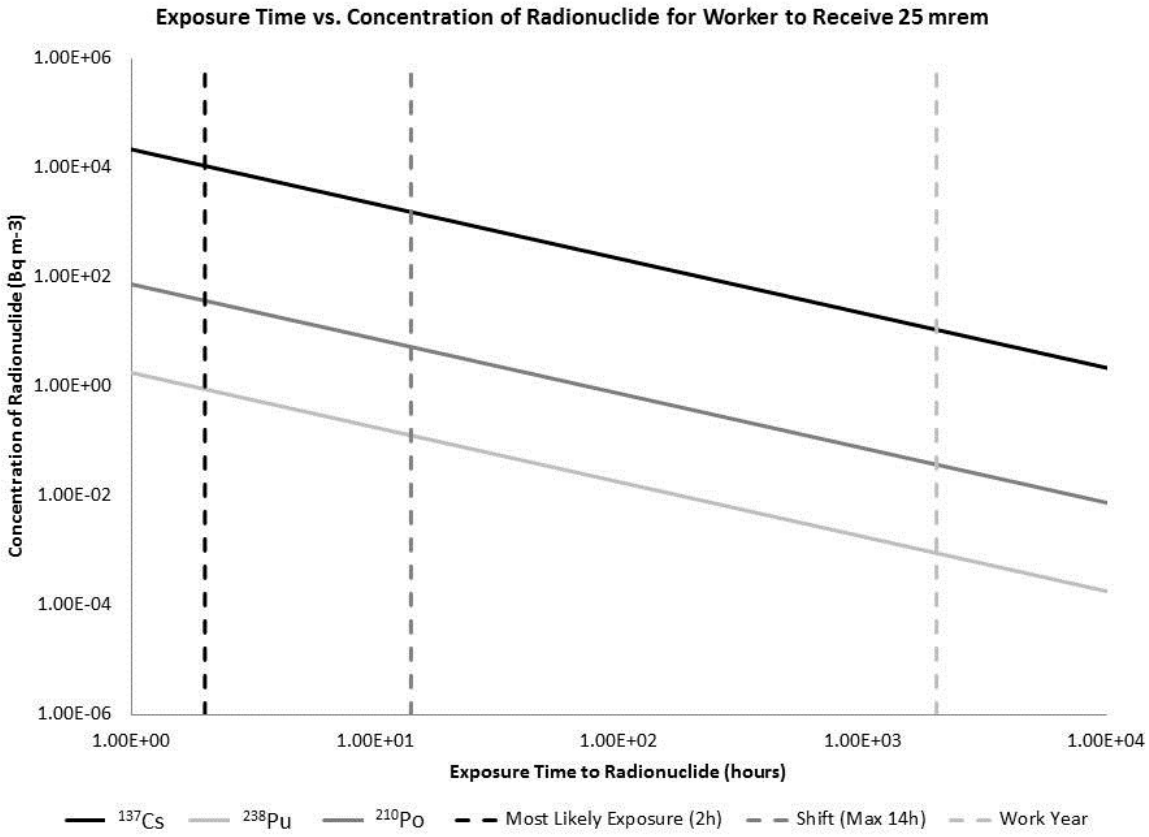

Figure 4: Radionuclide concentration levels vs. exposure times for a worker dose guideline level of 0.25 mSv. The threshold lines are extended to a 2000 h work year for comparison only.

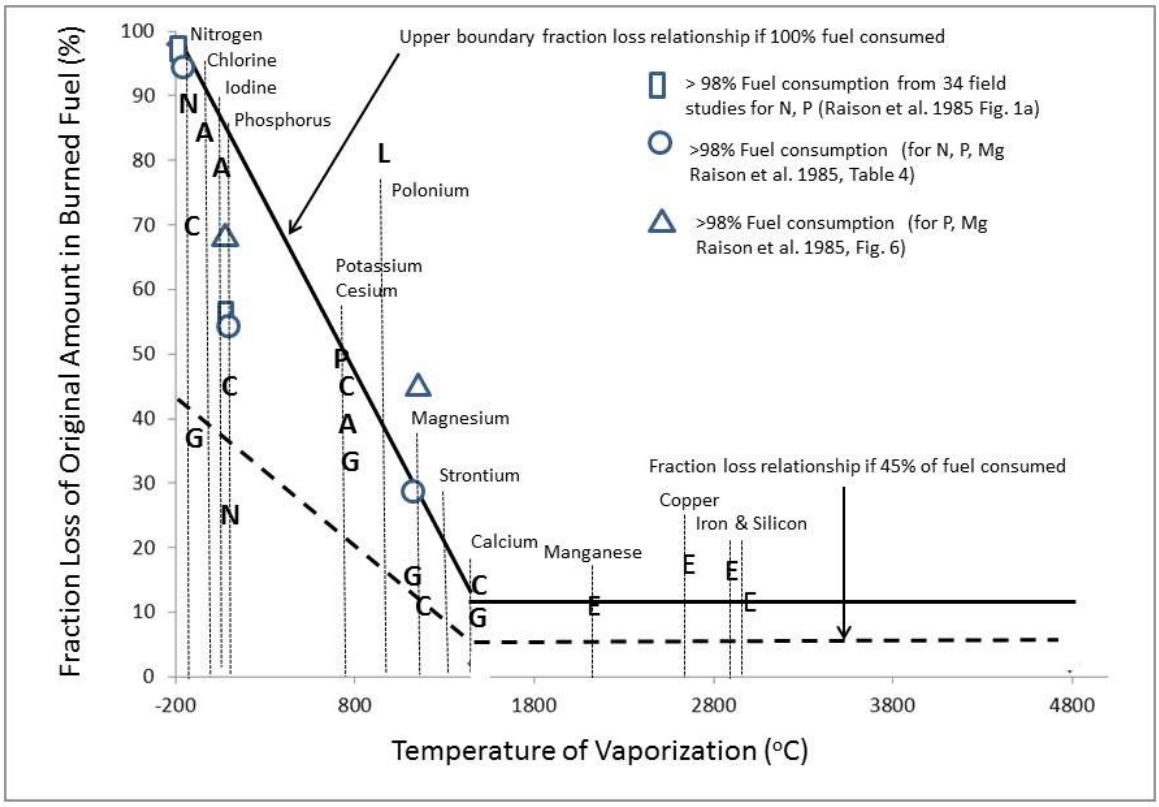

Figure 5: Fraction loss of elements in fire in relation to temperature of vaporization of elements. The upper boundary is based on Raison et al. (1985). Data from other studies are plotted along the elements temperature of vaporization line corresponding to Amiro et al. 1996 (A), LeCloarec et al 1995 (L), Palouris et al. 1995 (P), Niemeyer et al. 2005 (N), Christensen 1977 (C), Grier 1975 (G), and Evans and Allen 1971 at 590-750°C (E).

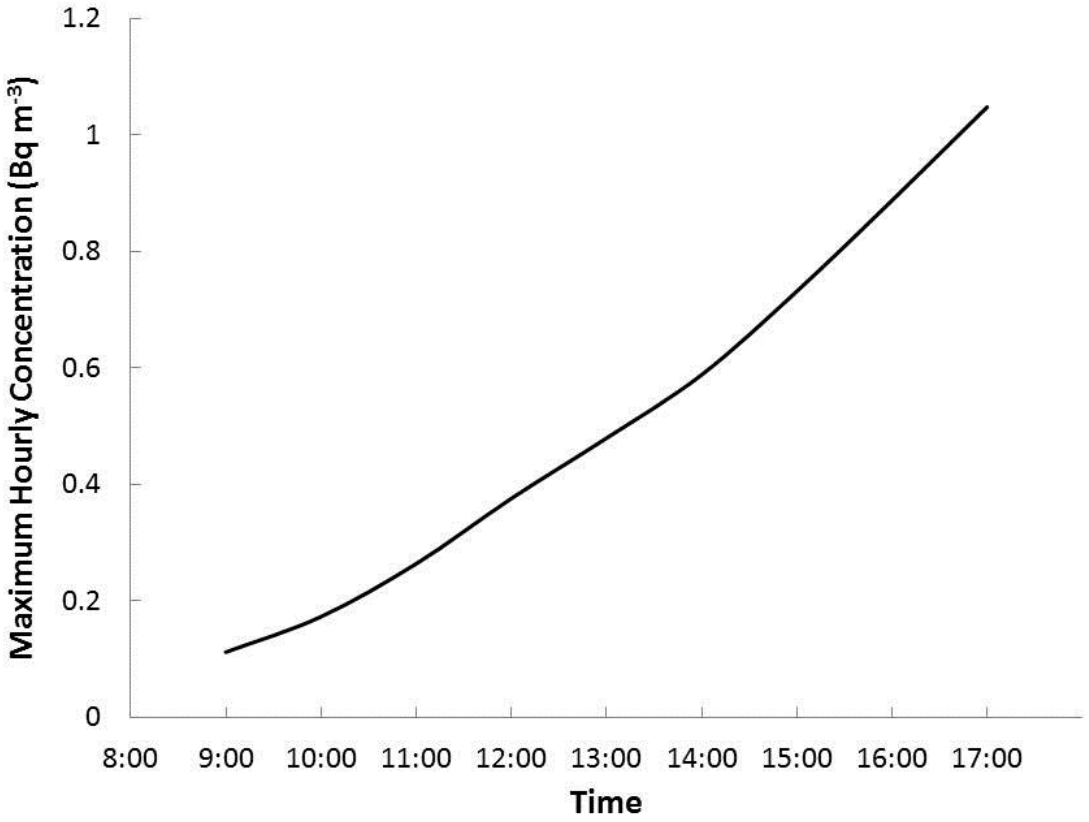

Figure 6: Hourly maximum concentration during a burn using the base-case scenario. As the fire grows larger and spreads quicker through the day, the amount of radionuclides released also increases, leading to higher atmospheric concentrations.

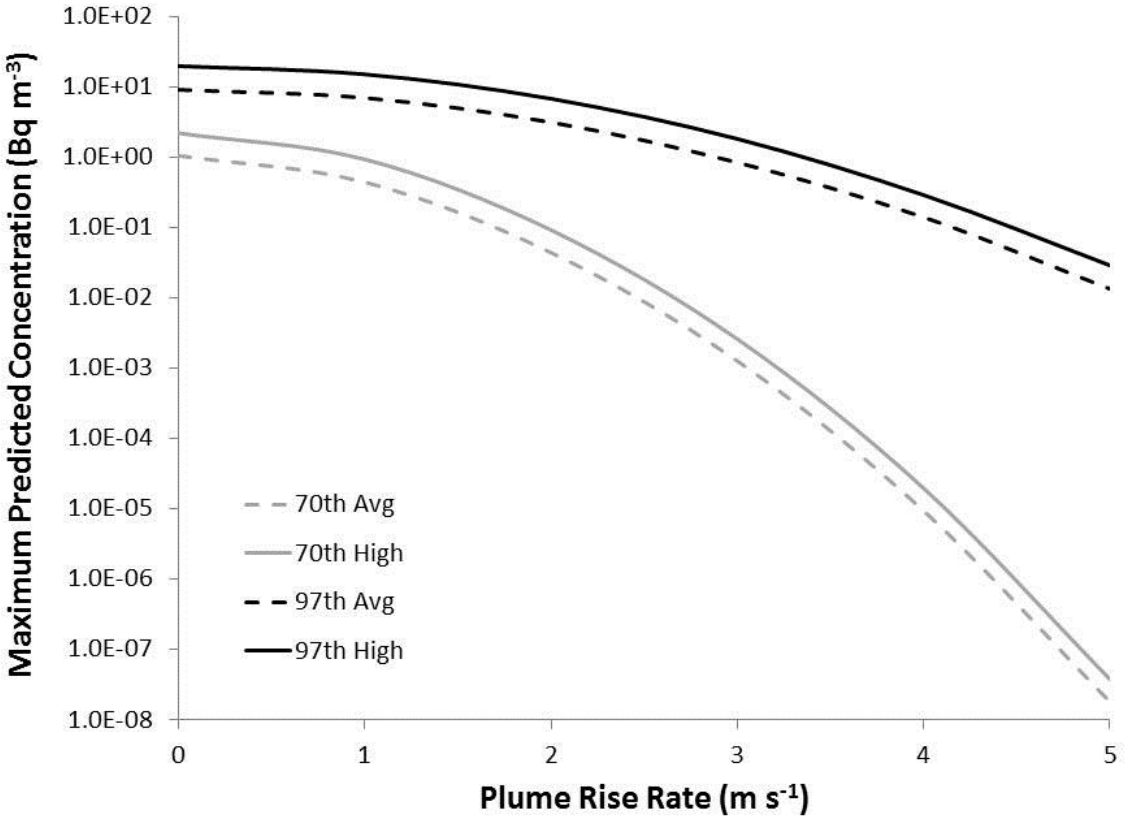

Figure 7: The maximum predicted concentration change for each scenario as a function of plume rise rate. The 70th and 97th percentile environmental conditions and the average (avg) and 95% (high) fuel loads correspond to values in Table 3. The concentration at a plume rise of zero 90) is the represented by the base case conditions of 1092.5 Bq kg^{-1} and fraction loss of 1.0.