

## Chapter 12

### **Vegetation Fires, Smoke Emissions, and Dispersion of Radionuclides in the Chernobyl Exclusion Zone**

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#### **Abstract**

The accident of the Chernobyl nuclear power plant (ChNPP) in 1986 was probably the worst environmental disaster in the past 30 years. The fallout and accumulation of radionuclides in the soil and vegetation could have long-term impacts on the environment. Radionuclides released during large, catastrophic vegetation fires could spread to continental Europe, Scandinavia, and Russia. The potential for large fires occurring in the Chernobyl Exclusion Zone (EZ) was assessed based on vegetation conditions. We reviewed the composition of radionuclides in the soil and vegetation and in the particulate matter emitted by fires. The highest atmospheric radionuclide  $^{137}\text{Cs}$  levels occurred in early spring and late fall, corresponding to the most intense periods of burning in the EZ. It is evident from satellite images that smoke plumes from the EZ and southern Ukraine dispersed several hundred kilometers from the active fires and reached a major metropolitan area. We propose to install a satellite receiving station to detect fires in real time. It is also essential to develop a smoke dispersion and air quality forecasting model to predict the radioactivity levels downwind from catastrophic fires in order to protect public health.

#### **12.1. Introduction**

The explosion of the No. 4 reactor of the Chernobyl nuclear power plant (ChNPP) in Pripjat, Ukraine, on April 26, 1986, created the worst nuclear accident in history. The reactor burned for 10 days and caused

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high concentrations of radionuclides over most of Europe, especially in Ukraine, Belarus, and western Russia. The International Atomic Energy Agency of the United Nations reported that 56 deaths were directly caused by the accident and nearly 4000 deaths could be related to the accident.

The Chernobyl Exclusion Zone (EZ) covers an area of 2600 km<sup>2</sup>. The EZ has a 154.5 km long international border adjacent to Belarus. About 70% of the territory is boreal forest, which is dominated by Scots pine, and the other 30% is mostly agricultural land. The forest provides multiple functions for the ecosystems of the EZ. It stores the radionuclides from the smoke plume fallout during the accident, absorbs the radionuclides from contaminated soil, and stabilizes the mobility of radionuclides. The concentrated radionuclides in the vegetation and soil would be emitted to the atmosphere during vegetation fires, which could lead to serious environmental damage. However, there was no active forest and fire management after the accident because the forest was contaminated by radionuclides and had limited commercial use. Scots pine stands became overstocked and stressed, predisposing them to attack by insects and diseases. The lack of fire management allowed the vegetation to overgrow, creating conditions favorable for fires to ignite and spread. About 12,000 hectares (ha) were burned in 1992, which led the Chernobyl State Enterprise to develop a fire surveillance system using lookout towers and reconnaissance planes. Hence, the region has not experienced a large fire in the past 15 years due to improved surveillance and aggressive, efficient fire suppression. During this period, fire activity has been largely limited to small fires in areas of formal agricultural land and settlement. The number of fires and total area burned have been declining since 1995. In 2005, only 36 ha were burned.

Since the nuclear accident, tremendous international efforts have been made to understand the impacts of radioactivity on ecosystems and human health. However, there are limited studies evaluating the potential risks of forest fires, the exposure levels of radionuclides from vegetation fires in the EZ, and the long-range transport of smoke plumes to large cities (e.g., Kiev) and across international borders to neighboring countries (e.g., Belarus, Russia, Poland). In this chapter, we will review the fire risks and the radioactivity levels in the soil, vegetation, and atmospheric particulate matter. We will show the satellite observation of long-range transport of smoke plumes from the EZ.

## 12.2. Fire risks

Although fire suppression in the Chernobyl EZ has been successful, budget limitation and the inability to utilize contaminated wood have

inhibited implementation of an active forest management program to reduce the amount of fuel in the forest. The dense spacing of trees within the forest limits the growth of understory vegetation; the forest floor is largely litter. This fuel structure causes fires to remain close to the ground with relatively short flame lengths and without the means of transitioning to large crown fires except under extreme weather conditions. However, as mature trees die and more sunlight reaches the forest floor, small young trees and some shade-tolerant trees will grow in these spaces. This forest succession process will result in more ladder fuels on the forest floor, increasing the risks of large crown fires.

In the EZ, certain areas are especially vulnerable to fires. For instance, because of limited forest management, Scots pine stands are overstocked, stressed, and susceptible to insects and diseases. The gypsy moth (*Lymantria dispar*) has prospered causing root rot that has killed a large portion of trees, including a 400-ha stand. The infected forest is highly susceptible to fires. Many trees have fallen in areas that burned in 1995, creating openings in the forest canopy that have allowed sunlight to reach the forest floor. This progression has introduced new fuel in the understory from seedling and shrub establishment. The blend of new undergrowth vegetation with large, downed trees provides fires an avenue to reach the crowns of the canopy. Hence, future fires could be more intense than previous fires in the EZ with higher flame lengths, longer burning time, and more smoke emissions. Catastrophic fires of this magnitude are difficult to control and pose safety and health hazards for firefighters and the general public.

The fire risks found in the EZ are quite common in many parts of the world. More than 70 million ha of federal land in the United States are characterized by heavy accumulation of understory vegetation, downed logs, and regrowth of secondary forest; conditions similar to the landscape in the EZ. The lack of proper forest management and the focus on fire suppression in the United States has been the major cause of many large, uncontrollable catastrophic fires in the western U.S. in the past eight years. These megafires usually occur under hot, dry, and windy conditions, burn for several weeks, and spread over thousands of hectares. Such catastrophic fires could also occur in the Chernobyl EZ if effective forest management is not implemented in the near future.

### 12.3. Radioactivity in soil and vegetation

The radioactivity of radionuclides  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{238}\text{Pu}$ , and  $^{239+240}\text{Pu}$  is concentrated mostly in the top layer of soil in the forests and grasslands

in Chernobyl (Yoschenko et al., 2006a). The radioactivity of each element varies considerably among the different components of the vegetation. The radioactivity of litter is higher than that in live foliage, bark, or live grasses.

The spatial distribution of  $^{137}\text{Cs}$  radioactivity levels on the surface layer of contaminated soil in December 2002 is shown in Fig. 12.1. The radioactivity is the highest within a 10 km radius of the ChNPPs. The spatial distribution of the soil contamination closely follows the prevailing winds (easterly and southerly) during the accident. Seventy percent of the radioactivity was blown to Belarus, covering about a quarter of the area in Belarus and causing a high incidence rate of children's thyroid cancer.

#### 12.4. Radioactivity of atmospheric particulate matter

There are two major sources of atmospheric radionuclides  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{238}\text{Pu}$ , and  $^{239+240}\text{Pu}$  in Chernobyl: smoke particles and mineral dust. Construction and windy conditions are the major causes of dust from contaminated soil. Dust particles are usually large (range: 2–100  $\mu\text{m}$  in diameter, mean:  $\sim 10 \mu\text{m}$ ) (Brasseur et al., 1999) and redeposit close to the source. In contrast, forest and grassland fires emit fine particles with a bimodal size distribution of 0.04–0.07  $\mu\text{m}$  and 0.1–0.3  $\mu\text{m}$  (Chakrabarty et al., 2006). While large particles are usually repelled by the respiratory system, fine particles are inhaled into the lungs. Fine particles in smoke plumes often form large particles in aged plumes through coagulation with cloud droplets downwind from the fires.

The radioactivity levels of  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{238}\text{Pu}$ , and  $^{239+240}\text{Pu}$  for atmospheric particulate matter near an experimental forest fire and two grassland fires in Chernobyl were found to be several orders of magnitude higher than the ambient levels (Yoschenko et al., 2006a). The estimation from an atmospheric transport model suggested that a small percentage of the radionuclides in the litter was emitted to the atmosphere during forest fires, and less than 1% of the radionuclides in the vegetation was emitted during grassland fires (Yoschenko et al., 2006b). The emitted radionuclides were concentrated in fine particles, which would increase the inhalation dosage to firefighters. The plutonium nuclides were the dominant radioactive elements of the fine particles.

The Chernobyl Radioecological Centre of the State Specialised Scientific and Industrial Enterprise (SSSIE “Ecocentre”) has been operating an automated monitoring network to measure the  $^{137}\text{Cs}$  radioactivity of particulate matter in the atmosphere within the EZ.

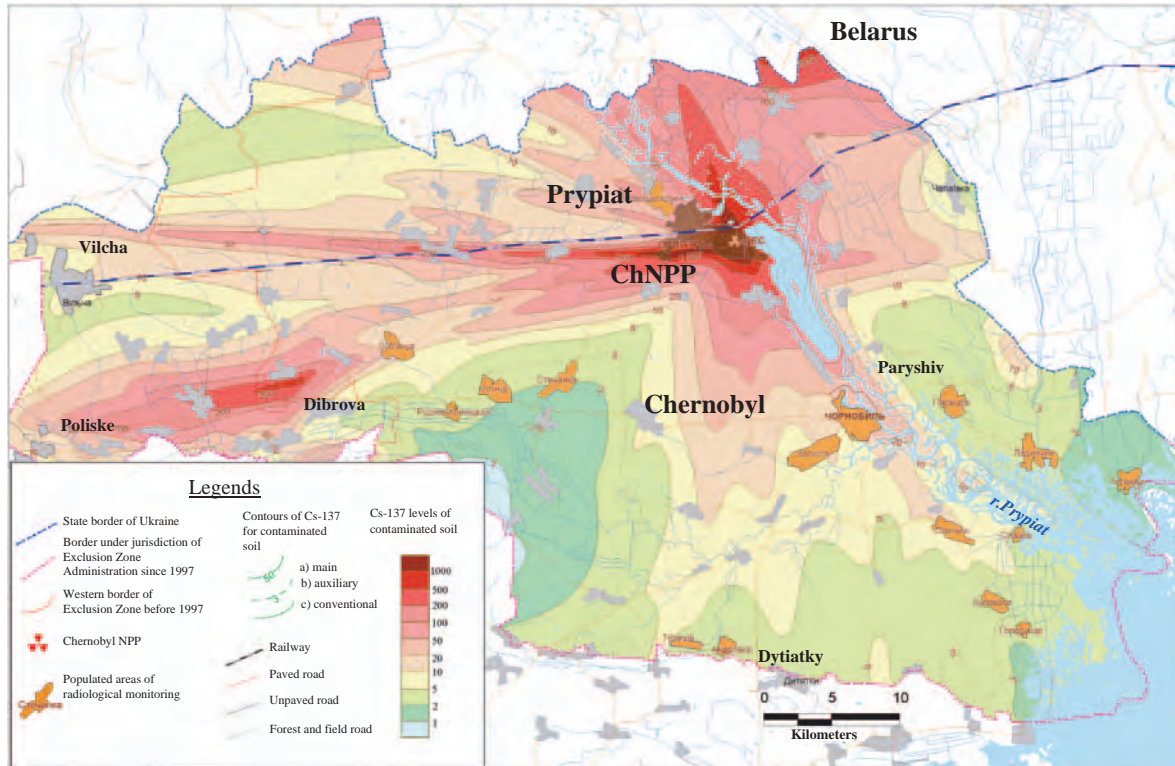


Figure 12.1.  $^{137}\text{Cs}$  radioactivity on the surface layer of contaminated soil in the Chernobyl Exclusion Zone in December 2002 (scale in kilometers).

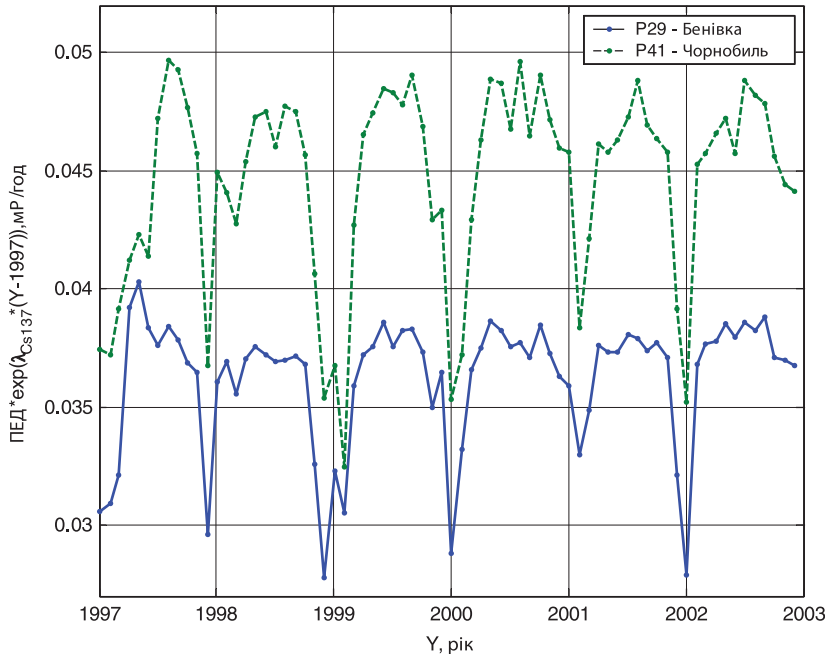


Figure 12.2. Monthly average  $^{137}\text{Cs}$  radioactivity of atmospheric particulate matter at two monitoring stations of the Chernobyl Exclusion Zone from 1997 to 2003. P29: Benivka village; P41: Chernobyl; x-axis: years; y-axis: exposure rate ( $\gamma$ ,  $^{37}\text{Cs}$  since 1997), mP per year.

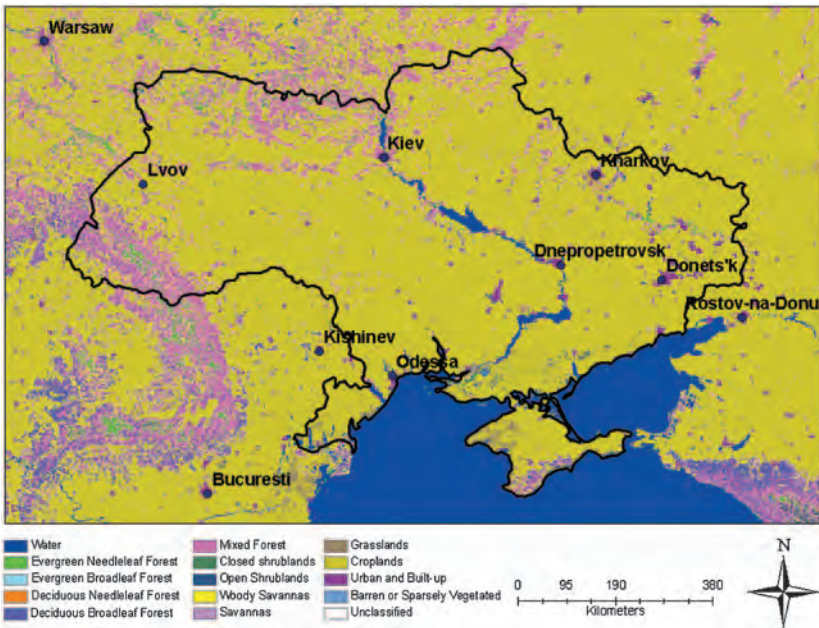
Figure 12.2 shows the monthly ambient cesium radioactivity measured at two stations in the SSSIE network: Benivka village (P29) and Chernobyl (P41). The  $^{137}\text{Cs}$  radioactivity levels in Chernobyl are about 20–30% higher than those at the Benivka village. The radioactivities at both sites increased several times in the early spring and late fall of each year, corresponding to the periods of most intense burning. The ambient radioactivities at both stations remained relatively stable between 1997 and 2003.

### 12.5. Long-Range transport of smoke plumes

In addition to being inhaled by humans close to the fires, fine particles emitted from fires can be transported hundreds to thousands of kilometers from large fires. Smoke plume dispersion depends on the vegetation type burned, fire intensity, burned areas, duration of the fires, plume heights, and meteorological conditions. Cropland dominates the

landscape in Ukraine, accounting for about 80% of the total area (Fig. 12.3) with mixed forests comprising the other 20%. Vegetation fires are widespread in Ukraine especially during the spring. These fires are often caused by human activities, such as clearing of agricultural residues before plowing the soil in the spring. Figure 12.4 shows the spatial distribution of fires and smoke in Ukraine and neighboring countries on April 16, 2006. Smoke plumes originating from active fires south of Kiev traveled north about 100 km.

The long-range transport of smoke plumes produced by fires in the Chernobyl EZ was observed by the U.S. National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite on May 8, 2003 (Fig. 12.5). The satellite image showed that the smoke plumes of a spring fire in the EZ reached Kiev, a city with a population of 2.7 million. The accumulation of understory vegetation and downed trees over the past 20 years has increased the probability of crown fires. Large, intense crown fires often



*Figure 12.3.* Land cover map in Ukraine and neighboring countries (The data are downloaded from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) MOD12 Land Cover and Land Cover Dynamics Products: [www-modis.bu.edu/landcover/userguide/c/intro.html](http://www-modis.bu.edu/landcover/userguide/c/intro.html)).



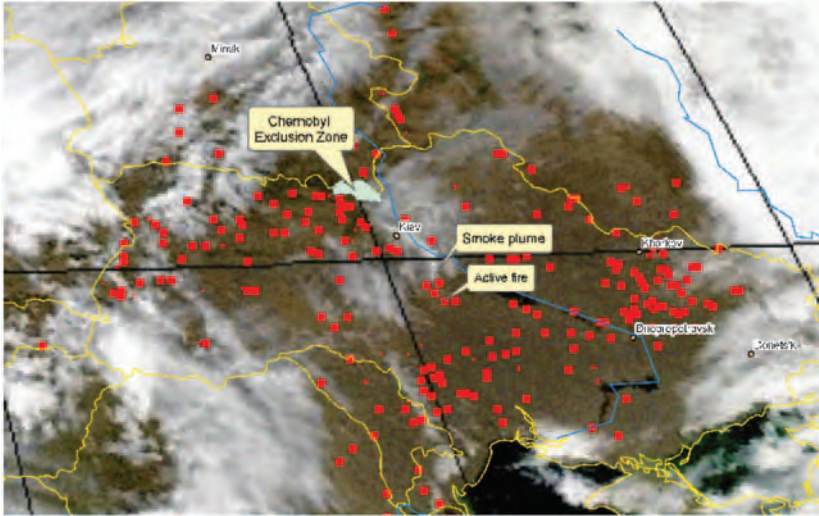


Figure 12.4. The MODIS satellite image of fire locations (red dots) and smoke in Ukraine and its neighboring countries, April 16, 2006.

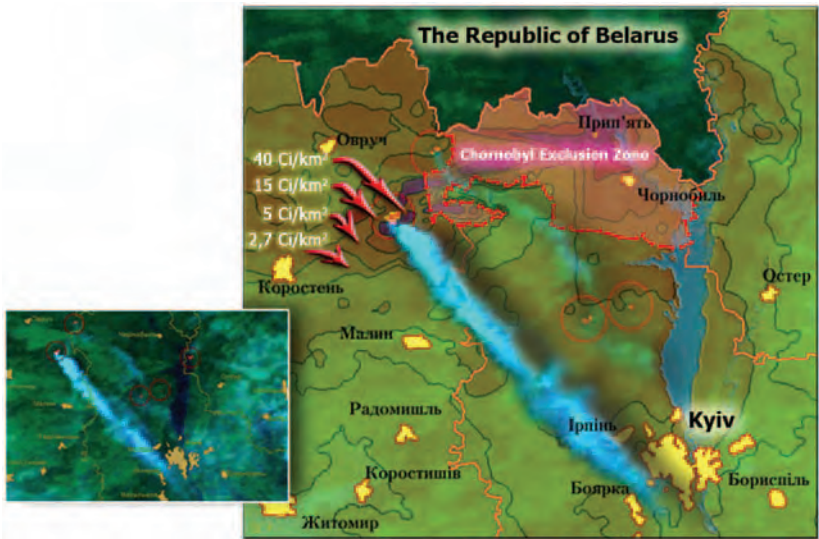


Figure 12.5. The NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite image (small figure) of a smoke plume in western Ukraine, May 8, 2003, overlaid on a land cover map (large picture) (courtesy of the Ukrainian Land and Resource Management Center).



create highly buoyant smoke plumes which penetrate the free troposphere and undergo long-range transport (Fig. 12.5).

The long-range transport of Chernobyl's smoke plumes not only were observed by the satellites but also may be detected by the ground radioisotope monitoring stations in Sweden. During the 1972–1985 period, the monthly  $^{137}\text{Cs}$  levels peaked in May, which were caused by the nuclear test fallout in the stratosphere (Kulan, 2006). However, during the 1987–2000 period, the  $^{137}\text{Cs}$  levels peaked in April and October, which coincided with the periods of most intense burning in the EZ. The resuspension of mineral dust in Chernobyl may also have contributed to the elevated  $^{137}\text{Cs}$  levels (Kulan, 2006).

## 12.6. Conclusion

The uncontrolled growth of understory vegetation, fallen trees, and the lack of forest management since the accident in 1986 have created conditions favorable for catastrophic fires in the Chernobyl EZ. These megafires are likely to occur under extremely dry and windy conditions, similar to the large fires that occurred in the western U.S. in the past eight years. Smoke plumes from these fires may spread radionuclides across continental Europe, Scandinavia, and Russia. To mitigate the impact of any future catastrophic fires in the EZ, we recommend the following improvements in fire detection and the development and implementation of a real-time smoke and radionuclide dispersion forecasting system.

### 12.6.1. Real-time fire detection

One of the major difficulties in monitoring and suppressing multiple fires over a large area is obtaining updated fire intelligence in real time. The information is essential for firefighters to locate fires and prioritize deploying firefighting equipment. We propose installing a Moderate Resolution Imaging Spectroradiometer (MODIS) direct broadcast satellite receiving station to monitor the fire locations, burned areas, and fire intensity. The system will complement the existing fire detection network.

The satellite receiving station automatically receives, processes, and archives MODIS data in real time from NASA's Terra and Aqua satellites. Data from the daily MODIS overpasses provide two daytime (13:00 and 14:30 local time) and two nighttime (1:30 and 23:00 local time) snapshots for each location in most of western Russia, continental Europe, and Scandinavia. It takes approximately 40 min to retrieve and

process the original MODIS data and generate fire locations at a  $1 \text{ km} \times 1 \text{ km}$  resolution. The fire products can be posted on the web site shortly after the satellite overpasses, enabling fire managers to access the information online. The MODIS instrument on the Terra and Aqua satellites not only detects fires but also detects smoke plumes with a more accurate spatial resolution than the NOAA AVHRR satellite.

The MODIS system can be used for monitoring the spatial and temporal distribution of fires, smoke, vegetation, and flooding not only in the EZ but also in the entire Ukraine and parts of the neighboring countries.

#### *12.6.2. Forecasting of smoke-radionuclide dispersion*

We recommend developing and installing a smoke dispersion forecasting system in Kiev. One such forecasting system currently under development is the Weather Research and Forecasting–Smoke Dispersion model (WRF–SD). The WRF–SD system forecasts the emission, transport, and transformation of atmospheric pollutants from vegetation fires. The WRF–SD modeling system is composed of fire products derived from real-time MODIS satellite data, a fire growth prediction model, the First Order Fire Effects Model (FOFEM) fire emissions model, and the Weather Research and Forecasting model with photochemistry and particulate matter modules. MODIS observations will be used to identify active fire locations and perimeters and measure the growth of burn areas. The MODIS derived fire products are used in conjunction with data on fuel characteristics, pollutant emissions factors categorized by fuel type, and meteorological conditions as input for FOFEM and the fire growth prediction model. FOFEM simulations provide a history of estimated smoke emissions for all wildland fires observed by MODIS in the most recent 24-h period. The fire growth simulations will provide a 48-h forecast of hourly fire growth and smoke emissions for large wildland fires. The daily emission inventories and forecasts of fire behavior and smoke emissions will provide input for WRF–SD. Nationwide 24- to 36-h forecasts of smoke dispersion and pollutant concentrations resulting from active large fires will be generated using WRF–SD.

The accident of the ChNPP has tremendous implications in today's world. The rapid expansion of nuclear energy and the proliferation of nuclear power plants increase the likelihood of future nuclear accidents. The emissions of radionuclides during the accidents will have immediate, catastrophic damages to the environment. However, the fallout of the radionuclides from the accidents, which are deposited on the soil and

vegetation, will have significant long-term environmental impacts. Subsequent vegetation fires, which may occur many years after the accidents, will release the radionuclides and potentially disperse the pollutants over a large area.

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