Existing Risks of Forest Fires in Radiation Contaminated Areas: A Critical Review

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Abstract. The purpose to highlight and focus on the most important risks of forest fires in radiation-contaminated areas, with some detailing of the problem in the Chernobyl Exclusion Zone (CEZ). The search strategy was to collect a sufficient number of relevant publications in ScienceDirect, PubMed, Mendeley, ResearchGate, GoogleScholar from 2006 to the present in English, Russian, Ukrainian. Requests were made on the topics "Forest fires in a radioactively contaminated area" and "Assessing the territories' radiation safety", as well as for the keywords of this study. Analysis of available open information about the CEZ was done. Although, in the future, temperatures are expected to rise in contaminated forests, and the amount of precipitation will remain the same or slightly decrease, which will contribute to an increase in the frequency of fires. Considering the socio-economic situation in Ukraine, the introduction of early detection systems is more profitable than the elimination of the consequences of such emergencies. Investigations have been studied, which were published after 2006 only in English, Russian, and Ukrainian. The most attention is paid to Chernobyl Exclusion Zone. Despite the fact that a lot of studies are devoted to the study of the ecological situation in radioactively contaminated areas, many issues related to safety still concern the population living in this area. The reason for this is intermittent fires, which again and again cover large areas with smoke and cannot be extinguished for a long time. To eliminate anxiety, it is necessary to convey truthful information to the population in the most accessible and convincing way. It was a critical look at numerous studies in this area that made it possible to present concentrated information understandable for most segments of the population. The document concentrates on the most key problems of fires in radioactive forests, shows the intensity of the radionuclides impact on the population and the exposure ways, as well as the probable risks. Such information is necessary to reduce the psychological stress that can be caused by the media influence. Objectively understood situation promotes constructive action in extreme conditions and reduces the likelihood of panic.

Keywords: Chernobyl, forest fire, radionuclides, risks, perspective.

1. Introduction

Forest fires negatively affect ecological systems. A forest fire is understood as the uncontrolled burning of a forest area. The forest area, over which the fire spreads, includes open forest areas (clearance, burnt out place, etc.). It is estimated that in Ukraine, on average, about 3.5 thousand forest fires occur annually, which destroy more than 5 thousand hectares of forest. Table 1 shows the data of forest fires in Ukraine in the period from 1993 to 2019.

Table 1. Dynamics of forest fires in Ukraine (MNS Ukrayiny)

Year	Number of forest fires, pcs.	Burnt area, ha	Year	Number of forest fires, pcs.	Burnt area, ha
1993	2967	3178	2007	6100	13787
1994	7396	10023	2008	4042	5529
1995	3758	3537	2009	7836	6315
1996	4908	12624	2010	3240	3668
1997	2308	1466	2011	2526	1049
1998	3906	4408	2012	2163	3478
1999	6035	5475	2013	1113	418
2000	3696	1618	2014	2003	13778
2001	3205	3772	2015	3813	14691
2002	6383	4983	2016	1249	1249
2003	4527	2833	2017	3131	5939
2004	1876	595	2018	1297	1367
2005	4223	2325	2019	1261	1065
2006	3842	4287			

A similar situation is observed in other countries of the world. For example:

- In the period 1990-2003, 84 large forest fires were registered in Greece, which exceeded 1000 ha (Dimitrakopoulos et al., 2011);

- From 1990 to 2013, 27273 fires were registered in Portugal, an average of 1136 fires burn 107 hectares per year (Tonini et al., 2017).

Also, numerous fires are recorded in other European countries (Modugno et al., 2016), in Latin America (Armenteras et al., 2017), in Africa (Kganyago et al., 2021), etc. So the problem is common and no continent or country is an exception.

The situation with forest fires becomes most unfavourable if a fire occurs in an area contaminated with long-lived radionuclides like ^{137}Cs (half-life 30.1 years) and ^{90}Sr (half-life

29.1 years), as a zone contaminated as a result of the Chernobyl accident. This is due to the fact that since the accident at the 4th unit of the Chernobyl nuclear power plant, a very slow natural clearing of radioactive contamination has been observed. The ^{137}Cs removal, as an environmental indicator, is less than one percent per year (MAGATE, 2008). At the same time, climate and land use changes have increased the risk of large forest fires in the Eastern European region, including the transboundary territories of Ukraine and Belarus contaminated with radionuclides (Evangeliou et al., 2015). As reported the Regional Eastern European Fire Monitoring Centre (REEFMC), more than 1147 wildfires on the territory of the Chernobyl Exclusion Zone (CEZ) occurred in 20 years (from 1993 to 2013) (Dvornik et al., 2018; Zibtsev et al., 2015).

As you know, forest ecosystems were one of the main ecosystems polluted by the Chernobyl precipitation. More than 60% of the forest lands in the Ukrainian and Belarusian exclusion zones are pine forests, mainly *Pinus sylvestris* L. The litter formed in the pine forest is the main combustible material for forest fires and, as reported in (Agapkina et al., 1995; Ipatyev et al., 1999), it can concentrate up to 90% of radionuclides from their total amount in the forest ecosystem.

In this regard, the purpose of current paper is to highlight and focus on the most important risks of forest fires in radiation-contaminated areas, with some detailing of the problem in the CEZ.

2. Materials and Methods

2.1. Review of sources

The search strategy was to collect a sufficient number of relevant publications in ScienceDirect, PubMed, Mendeley, ResearchGate, GoogleScholar from 2006 to the present in English, Russian, Ukrainian. Requests were made on the topics "Forest fires in a radioactively contaminated area" and "Assessing the territories' radiation safety", as well as for the keywords of this study. Additional publications were identified from the references in the discovered publications and from the authors' own files.

2.2. Some information about the CEZ

The exclusion zone and the zone of unconditional (obligatory) resettlement is a part of the territory that has undergone the greatest radioactive contamination due to the Chernobyl disaster, with a special form of management, the lands of which have been taken out of economic circulation. The geographic location of the CEZ is shown in Figure 1.

The main routes of migration of radionuclides outside the CEZ are:

- water (river) runoff (Pripyat river) - about 65%;
- in case of fires - 24%;
- air (wind) transfer - 10%;
- technogenic migration and biogenic removal - 0.5% each (Azarov et al., 2016; Khan et al., 2019a).

Table 2 shows data on the radioactive contamination of various objects and territories of the CEZ (Azarov et al., 2016).

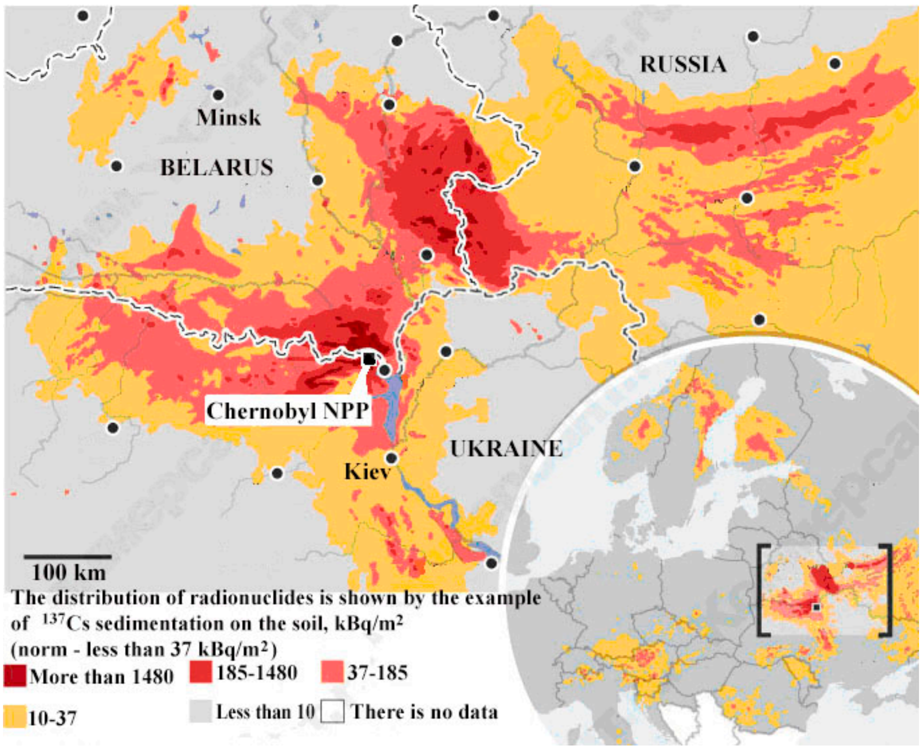

Figure 1. The Chernobyl Exclusion Zone (https://www.kommersant.ru/projects/chernobyl)

Table 2. Stocks of radionuclides in various objects and territories of the CEZ (Azarov et al., 2016)

Object/territory	Activity, Bq			Area
	^{137}Cs	^{90}Sr	TУЕ	
The territory of the Chornobyl zone	$1.44 \cdot 10^{13}$	$6.4 \cdot 10^{11}$	$2.6 \cdot 10^{10}$	2044 km^2
Forests	$8.4 \cdot 10^{13}$	$3.7 \cdot 10^{11}$	$1.5 \cdot 10^{10}$	768 km^2
Former farmland	$6.1 \cdot 10^{13}$	$2.7 \cdot 10^{11}$	$1.2 \cdot 10^{10}$	484 km^2

Radioactive waste protection point	$1.4 \cdot 10^{14}$	$8.2 \cdot 10^{12}$	$3.3 \cdot 10^{11}$	800 pcs.
Shelter Object	$1.3 \cdot 10^{14}$	$7.4 \cdot 10^{13}$	$2.7 \cdot 10^{12}$	1 pcs.

Forests occupy 45% of the territory of the Exclusion Zone (102 thousand hectares). In terms of forest-growing zoning, they belong to the Polesie zone of Ukraine and are located in Novoshepelivsko-Vilchansky and Pripyatsko-Dneprovsky floodplain-pine forest areas. Preferred landscapes here are above-floodplain terraces, watershed plains and river valleys.

During the time after the Chernobyl disaster, more than 1147 fires of a different nature occurred in the 30-kilometer zone, as a result of which 3092 different buildings and about 25,000 hectares of forests and former farmland burned down. The most large-scale fires occurred in August 1992 on a total area of 17000 hectares of meadows and forests, including a crown fire on an area of more than 5000 hectares (Kyyivsʹka oblastʹ). There are many concerns about the increased frequency of large forest fires in contaminated areas, including exposure to radionuclides during a fire and long-range transport of re-suspended radionuclides in smoke plumes (Jones et al., 2020; Evangeliou et al., 2016).

In the absence of traditional economic activity in the exclusion zone, for 30 years there has been an intensive accumulation of hazardous combustible material in forests and meadows. Excessively high density of stands in pine forests throughout the Exclusion Zone, different ages of trees and the presence of young trees at forest edges increase the risk of high-intensity upstream large-scale wildfires.

3. Results and Discussion

3.1. Causes of forest fires in radioactively contaminated areas and related problems

As studies show, more than 90% of all cases occurred due to anthropogenic factors (Dvornik et al., 2017). Fires occur due to vehicles, machinery, power lines, arson and other anthropic factors (Dvornik et al., 2017, Vambol et al., 2019a). The most flammable period is April-May. So, in the spring, on average, 52% of all fires occur in the forests of the country annually, which cover about 800 hectares of the total area of fires (Azarov et al., 2016). This time coincides with the beginning of agricultural work, and a significant number of forest fires arise from agricultural arson and the burning of dry vegetation. This situation is no exception, as in many developing countries, due to demographic changes and increasing pressure on plant resources, the use of fire as a tool for land clearing has increased rapidly over the past few decades (Goldammer et al., 2008). Due to difficult economic conditions and different political situations in some countries of Eurasia, the ability to effectively manage forest fires has diminished to such an extent that fires are becoming almost uncontrollable (Goldammer, 2006). Thus, if a fire covers large areas and cannot be easily extinguished with local equipment, there is the potential for a large-scale fire that cannot be extinguished even with air suppression. A similar situation is observed in Ukraine, where in the territories radioactively contaminated after the Chernobyl accident, the duration of fires can be several days (Azarov et al., 2016) due to insufficient resources for their elimination. The existing capacities, structure and location of fire fighting units in the exclusion zone do not correspond to such a high level of fire safety, do not guarantee a quick response and effective extinguishing in critical weather conditions. Thus, one fire and rescue unit, which has two or three obsolete vehicles with a limited amount of fuel and 5-7 fire-fighters, is responsible for an area of more than 65000 hectares. At the same time, outside the exclusion zone, a similar area of responsibility is about 15-20 times smaller. About a third of the territory of the exclusion zone is not covered at all by means of fire detection, there are no observation towers, and almost 23000 hectares of forests are inaccessible to fire fighting equipment (Azarov et al., 2016). All of the above factors cause a high risk of large-scale fires in the exclusion zone, the largest of which (since 1992) took place at the end of April 2015.

Another factor affecting the frequency and scale of forest fires in radioactively contaminated areas is the change in the landscape of the area in the CEZ. Due to the strong radioactive contamination of the territory, work on the processing of agricultural land, on the felling of trees (including young seedlings) was stopped there. This contributed to the consistent natural replacement of one biological community by another. The change in the region is evidenced by an increase in the area covered by forests, namely 70% now versus 53% before the disaster (IAEA, 2001). The pastures, where the farmers used to grow crops, are now occupied by woody species. Thus, the radionuclides have now moved to the forest soil and mostly remained there (Evangeliou et al., 2014). If trees or other permanent vegetation were absent, the pollutants would be carried away by dust or water to other areas. The intensity of the migration processes of radionuclides in forests is determined by a complex of biocenotic and biogeochemical factors, such as the process of sorption and desorption, movement with surface and subsurface composition, biogenic mixing, the effect of vegetation composition, as well as diffusion, deflation, and convective transfer. Trees, other plants and fungi trap radionuclides during their main life cycle. The behaviour of radionuclides in the soil and their entry into wood depends mainly on the properties of the soil (texture, acidity, humus content, etc.), as well as on the biological characteristics of plant species. Falling to the ground leaves and needles form a "carpet" and a continuous accumulation of dead wood and other plant material, which contributes to the return of radioactive salts to the topsoil (Evangeliou et al., 2014). Forest litter is the main conductor of combustion in forest fires (Kurbatskiy, 1962).

Experimental studies (Krasnov et al., 2007) show that in forest areas the main amount of radionuclides (more than 98%) are concentrated in the lower part of the forest litter and in the upper 10 cm soil layer. This is consistent with the work results (Dvornik et al., 2017), where it is said that more than 90% of ^{137}Cs is associated with forest litter, and more than 50% of the ^{137}Cs activity in litter is associated with needles. The situation with the accumulation of dead plant material is aggravated by a significant decrease in the rate of decomposition of its material (Mousseau et al., 2014). As a result of this development, the frequency of fires increases in this region (Evangeliou et al., 2014), and climatic anomalies such as droughts and high temperatures aggravate the problem of fires (Evangeliou et al., 2015; Azarov et al., 2016).

During forest fires in radioactively contaminated areas, radioactive combustion products and toxic gases enter the atmosphere, since all organic materials in contaminated areas contain radioactive material. Cesium-137 is one of the most dangerous radionuclides emitted after nuclear accidents because of its long half-life, the type of radiation it emits during decay and its bioaccumulation by organisms (Evangeliou et al., 2015; Woodhead, 1973). The concentration of combustion products depends on the surface heat flux emitted by the fire, the prevailing wind and precipitation regime, especially in the summer months from July to August, when the existing fire hazard is higher and, as a rule, significantly exceeds the maximum permissible values. Toxic gases that are released into the air pose a potential danger both for the local population and for employees of fire and rescue units who are directly involved in extinguishing fires (Evangeliou et al., 2015; Azarov et al., 2015a).

When burning 1 kg of pine, 4.9 m^3 of combustion products is formed at a temperature of 1290 K. Flame combustion of wood in air is possible provided that it contains at least 15% oxygen by volume. Table 3 shows the environmental indicators for the burning of coniferous stands on an area of 10 hectares (Grishin & Filkov, 2005).

Table 3. Environmental indicators in a forest fire (Grishin & Filkov, 2005)

The forest fire type	Flue gas temperature in the fire zone, K	Concentration of "flue gases" in air, mg/m^3				
		CO	CO_2	SO_2	NO_2	C, soot
Top fire	1100	800	1200	200	400	40
Weak ground fire	1250	1100	2050	450	520	60
Strong ground fire	1380	1600	4300	800	1000	80

Pyrogenic emissions also include substances such as K, Cl, SO_4, and heavy elements such as Cu and Zn (Andreae & Merlet, 2001). Radioactive iodine and cesium have been detected in fires smoke in the CEZ (Amiro et al., 1996; Yoschenko et al., 2006). Even at a distance of about 17 km from the burning forest, in the air an increase in the ^{137}Cs concentration was observed (Garger et al., 1998).

When conducting research, scientists give preference to different initial parameters characterizing forest fires in radioactively contaminated areas, for example, the ^{137}Cs concentration in the atmosphere surface layer, the precipitation density, the rate and coefficient of re-transition of settled radioactive material into the atmosphere (that is, resuspension) are taken into account, which can continue in the contaminated area for a long time, etc. The choice of these parameters depends on many factors: the fire type (top fire, ground fire, transitional) and the forest fire phase (initial, active, smouldering); physical and chemical properties of forest fuels; composition and age of radioactive deposits in forests; meteorological parameters (wind speed, humidity, temperature, season), etc. Thus, liquidators and forest workers involved in extinguishing fires are at risk of inhalation of aerosols, as well as internal radiation (for example, by swallowing).

3.2. Factors influencing the spread of fires and radioactive substances

According to some studies, large forest fires occur under the influence of strong winds, as in April 2020 (CEZ) (Evangeliou & Eckhardt, 2020), at high air temperatures and low relative humidity (Stocks et al., 2002; Millán et al., 1998; Wagner, 1977). Such conclusions are consistent with the study (Dimitrakopoulos et al., 2011), where it was found that of 84 large forest fires in Greece (burned area is more than 1000 ha), about 2/3 occurred at high air temperatures and moderately low relative humidity, and about 25% of large fires occurred in extreme heat. Indeed, it is observed that the climate near the Chernobyl nuclear power plant becomes more and more warm, and the amount of precipitation has stabilized or slightly decreased, this was most clearly manifested in the period from July to August 2010, when the temperature exceeded 40°C and there was no precipitation for many weeks (Evangeliou et al., 2014). It is highly likely that warming trends may already be contributing to increased pressures on boreal forests such as those prevalent in the Chernobyl region. An increase in the load on trees is associated with a lack of water and, as a consequence, increased stress for trees from drought (McDowell et al., 2008). Under such conditions, trees are more susceptible to subsequent fire damage (Van Mantgem & Stephenson, 2007), which actually contributes to an increase in fire intensity.

In addition to this, forest litter is the main conductor of combustion (i.e. fuel) during forest fires (Gormley et al., 2020; Yang et al., 2018). This also includes dry grass and mosses, lichens, fallen leaves, branches, fragments of bark, etc. (pine phytocenoses have 3–6 cm of forest litter). Finney et al. (2013) showed in their investigation that fuel moisture plays a dominant role in determining the speed of fire propagation.

One should also focus on one more factors, namely the presence of continuous and homogeneous patches in forests, which contributes to the spread of fires over large areas during extreme events (Cary et al., 2006). In (Evangeliou et al., 2015), using a map of the European tree cover, the relationship between the occurrence of fires and the land cover in Europe was investigated. It was found that the burnout largest area occurred in regions with less than 60% forest cover, while when forest cover exceeded 60%, the average area of burnout was low, and the 95th percentile remained high. A recent analysis of global changes in land cover showed that forest growth was the dominant trend in the CEZ in the period 2000–2012 (Hansen et al., 2013). Consequently, large fires can occur in regions with dense forests, such as in early April 2020 (CEZ), which lasts 22 days, which contributes to extreme releases of toxic and radioactive substances (Evangeliou et al., 2015).

The effects of fires can be significantly aggravated in contaminated regions due to the effect of radiation on the decomposition and growth of trees in the Chernobyl region (Mousseau et al., 2014). Characteristics and measured activity of ^{137}Cs in samples from experimental forest sites, which are presented in (Dvornik et al., 2017), show that more than 90% of ^{137}Cs is associated with forest litter. The content of ^{137}Cs in litter components ranges from 10% to 15% of its total activity in combustible materials. More than 50% of ^{137}Cs activity in litter is associated with needles (Dvornik et al., 2017) that are also stated in works (Evangeliou et al., 2015; Azarov et al., 2016). Radioactive contamination reduces the rate of decomposition of organic matter due to its negative impact on soil biota, as a result of which the litter layer in the most contaminated areas is about four times thicker than in the least contaminated areas around Chernobyl (Mousseau et al., 2014).

The active concentration of radionuclides in aerosols depends on several factors: the density of contamination of fuel materials, the intensity and duration of combustion, the area of forest fires and their intensity, the speed and direction of the wind (Dvornik et al., 2017). Thus, experiments have shown that the higher the density of radioactive contamination of fuel components, the higher the concentration of radionuclides in the air in the event of a forest fire. With a tailwind, high values of the concentration of radionuclides in the air can also be detected at an average distance (10 km) from the fire source (Dvornik et al., 2017).

Having risen into the air, air currents can carry combustion products, affecting their chemical transformation and fate. In their studies (Chin et al., 2002; Bertschi et al., 2004), the authors showed that the residence time of aerosol in the atmosphere and the effect of wind on the quality of surface air depends on the altitude at which the release occurs. At the same time, in the study of corona fires, the authors of (Andreae & Merlet, 2001; Lavoué et al., 2000) proved that many fires generate enough energy to raise clouds of smoke above the boundary layer to stratospheric heights due to convection of the supercell (Evangeliou et al., 2015; Fromm & Servranckx, 2003), which can contribute to the dispersion of pollutants and reducing the likelihood of their subsidence in the surface layer.

3.3. Air contamination and radioactive fallout

High-intensity crown fires in Chernobyl contribute to the release and transfer of large amounts of radioactive substances. The transfer of these emissions can reach hundreds and thousands of kilometres in the direction of the wind, including to settlements (Hao et al., 2008). Combustion produces solid products such as ash and incomplete combustion products and aerosols. During the burning of a forest loaded with radionuclides, radioactive substances such as plutonium, cesium, strontium, etc., are released into the atmospheric air in the form of small particles (Hao et al., 2008). Volatile radionuclides such as ^{134}Cs, ^{137}Cs, ^{132}Te, ^{133}I, together with fine dust particles ("aerosols"), are distributed in the atmosphere, although most of the radioactive iodine remains in gaseous form (Smith & Beresford, 2005). The study (Dvornik et al., 2018) made it possible to establish that the activity of long-lived radionuclides in solid combustion products exceeds the activity in fuel materials by 1.5–4 times (the largest ratio was 4.2 ± 0.4 for ^{137}Cs). In the process of combustion, forest materials lose up to 90% of their organic matter, and radionuclides are concentrated in the mineral part of combustion products and ash (Dvornik et al., 2018). Thus, solid combustion products are an open source of ionization with radioactive substances' potentially high activity that significantly affects the radiation safety level of the region. Radioactive substances re-suspended in the form of dust or smoke from forest fires can be inhaled by people living near contaminated areas. The main ways of penetration of toxic substances into the human body are the respiratory tract, skin, and digestive organs. The most important of these are the respiratory tract. Absorbed by the mucous membrane of the respiratory tract, toxic substances enter the bloodstream, bypassing the liver, which acts as a mechanical and biochemical barrier in the body (Azarov et al., 2016).

The authors of (Azarov et al., 2016) carried out field studies at distances of 7 and 15 km from the centre of a forest fire, in which the smoke jet reached a height of 1.2 km, and the length of the smoke plume was up to 20 km. The results showed that the volumetric activity of radioactive combustion products is mainly due to ^{137}Cs, which is 82% of the total activity, ^{90}Sr - 7%, and transuranic elements (TUE) - <1.0%. It was also found that in the surface layer of the atmosphere, smoke particles with an aerodynamic range of less than 1 micron, the most dangerous in terms of radiation for humans, prevailed.

The measured distribution of the volumetric concentration of radionuclides and the intensity of their sedimentation in the atmospheric air at various distances from a forest fire are shown in Figures 2, 3.

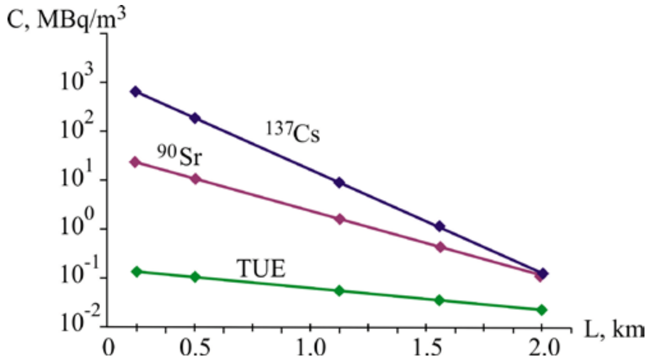

Figure 2. Distribution of the radionuclides volumetric concentration in the atmospheric air depending on the distance during the active phase of a forest fire

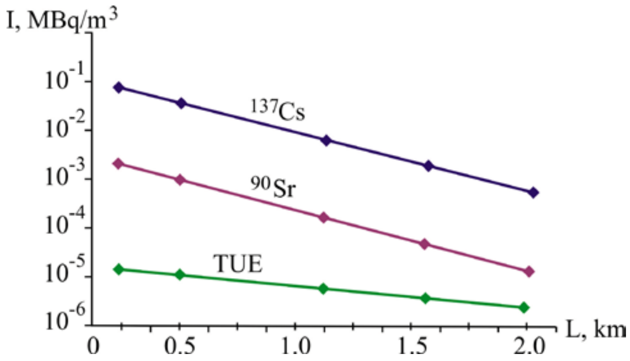

Figure 3. Distribution of the intensity of radionuclides precipitation in the atmospheric air depending on the distance during the active phase of a forest fire

In Figure 2 it is clearly seen that at a distance of 2 km from the forest fire, the volume concentration of ^{137}Cs decreased by three orders of magnitude and for ^{90}Sr only by an order of magnitude. Figure 3 that the intensity of the settling of smoke particles from the atmosphere to the soil surface will be determined mainly by two factors: "dry" gravitational turbulent sedimentation and washout by precipitation. In addition, the precipitation of smoke particles can occur due to moisture condensation and diffusion processes (Azarov et al., 2016). The authors of (Smith & Beresford, 2005; Smith & Clark, 1989) adhere to a similar point of view. Dry fallout of radionuclides occurs in three ways: fallout of heavier particles near the source; direct adsorption of gaseous elements on the earth's surface; and the collision of particles in the air with the surface. It is assumed that fine aerosol particles and gaseous elements are deposited at a rate proportional to their concentration in air (Smith & Clark, 1989).

In addition, the aspect of soil treatment in areas contaminated with radioactive particles is important, since contaminated soil particles re-suspended during agricultural work can enter the operator's body by inhalation or ingestion. The re-weighing of radioactive particles depends on many factors, primarily the amount of precipitation, humidity, wind speed, etc. The re-suspension is expected to decrease over time after precipitation, as radioactivity is transferred from the soil surface to deeper layers (Filipović-Vinceković et al., 1991).

3.4. Food contamination

The main contribution to land pollution (about 90%) is ^{137}Cs. While settling on the ground, ^{137}Cs accumulates in the upper soil layer and remains there for many years (Filipović-

Vinceković et al., 1991). This is confirmed by studies of soil samples taken after Fukushima and Chernobyl (Hashimoto et al., 2012), although compared to the 1991 data, the level of soil contamination has decreased by half (Herasymenko et al., 2018).

It is believed that the initial movement of radioactive substances to the soil surface occurs relatively quickly through precipitation. However, after this process slows down. Radioactive decay and migration of radioactivity in the soil significantly reduce the dose rate of external radiation over time after fallout. Studies have shown that the dose of external exposure to the population decreased by more than an order of magnitude from the end of 1986 to 1993, mainly due to the physical decay of relatively short-lived radionuclides (^{106}Ru, ^{134}Cs). After this period, ^{137}Cs makes the main contribution to the external radiation dose, although it should be noted that for several years after the Chernobyl accident, the bioavailability and mobility of radioactive cesium in the environment decreased markedly (Hao et al., 2008; Herasymenko et al., 2018), which contributed to significant changes in food and vegetation contamination and surface waters (Hao et al., 2008).

The amount and distribution of radioactivity in plant growth areas affects the transfer of radioactivity into the food chain and surface waters. Many Japanese researchers have cited serious food safety concerns in radioactively contaminated areas. Although it was revealed that in 2011 97% of the studied samples of agricultural products had radioactivity less than 500 Bq/kg (preliminary standard level) and only 3% contained more than 500 Bq/kg (Nihei, 2013). Other studies also confirm that food contamination levels were well below relevant international standards (Chiu et al., 2013; Itthipoonthanakorn et al., 2013).

Recent studies of the specific activity of ^{137}Cs and ^{90}Sr in vegetable crops grown in the territory of voluntary guaranteed resettlement and the territory of enhanced radiological control showed that the lowest ^{137}Cs activity in comparison with other vegetables was in potatoes, onions and cucumbers, in While in sweet peppers and zucchini the ^{137}Cs activity was twice as high, in carrots and tomatoes it was almost 4 times, in beets - almost 8 times, in beans - 10 times. The lowest level of ^{90}Sr activity is in onions, in tomatoes and cucumbers - twice as high, in sweet peppers - 4 times higher, in potatoes and cabbage - almost 10 times higher (Herasymenko et al., 2018) In both territories, the activity of ^{137}Cs and ^{90}Sr was the highest in cow milk and pork meat. An interesting fact is that in the spring-summer period the activity of ^{137}Cs and ^{90}Sr in milk was two to three times higher than in the autumn-winter period (Herasymenko et al., 2018). This is due to the fact that in the spring and summer period, cows graze on natural pastures, where the level of soil pollution is much higher than on arable land. It has been established that the redistribution of radioactive substances occurs during plowing to a depth of about 20-30 cm. As soon as radioactivity has penetrated into the soil and attached to soil particles, long-lived radionuclides such as ^{90}Sr, ^{137}Cs, ^{241}Am and Pu isotopes become relatively immobile in soils in over long periods of time (Hao et al., 2008). Low activity of ^{137}Cs and ^{90}Sr was observed in poultry meat, which consumes mainly grain and concentrated feed, where the accumulation of radionuclides is low. In general, the authors found that the activity of ^{137}Cs and ^{90}Sr in vegetable products, milk, and meat of personal subsidiary farms does not exceed permissible levels (Herasymenko et al., 2018). In particular, work (Lihtarov et al., 2012) it was also reported that the concentration of ^{90}Sr activities in cow's milk and vegetables did not exceed the Ukrainian permissible levels.

At the same time, experimental studies conducted from 2011 to 2019 (Labunska et al., 2021) demonstrate that the concentration of ^{90}Sr activity in grains exceeded the Ukrainian hygienic standard in 45% of 114 grain samples, while the total excess of ^{90}Sr and ^{137}Cs was detected in almost half (48%) of all of the 116 grain samples and analyzed over a 9-year period (two of the 116 grain samples were analyzed for ^{137}Cs only, but not ^{90}Sr due to sample loss). These conclusions are also consistent with the results of the study for 1997-2011, which also revealed an excess of the radioactivity of grain in half of the samples taken (Kashparov et al., 2013). The authors of (Salbu et al., 2018) believe that a number of factors can influence the transfer of ^{90}Sr from soil to grain, including the increased bioavailability of this radionuclide. However, the information on the transfer of ^{90}Sr into food crops is still insufficient for a complete understanding of the patterns of contamination of grown products.

3.5. Discussions about risks for fire liquidators and contaminated areas' residents

Assessing the available information on the frequency and intensity of forest fires in contaminated areas; factors contributing to their spread; air and food pollution, it is necessary to summarize the risks for fire liquidators and contaminated areas' residents.

Many researchers agree that, in addition to the external radiation dose from soil and vegetation, the inhalation intake of radioactive substances can make a significant contribution to the total dose (Azarov et al., 2016; Dvornik et al., 2017; Amiro et al., 1996; Garger et al., 1998; Evangeliou & Eckhardt, 2020; Syarbaini et al., 2019). A study of the release of radioactive particles into the air during a forest fire in Riau Province, Indonesia indicates that smoke from forest fires contains radioactive particles, which poses a potential threat to public health. Inhaled smoke particles from forest fires can increase the radiation doses to the population (Syarbaini et al., 2019). At the same time, the contribution of inhalation intake can reach from 50% (Yoschenko et al., 2006) to 72% of the total dose (Evangeliou & Eckhardt, 2020), although it should be noted that the total time of fire-fighters work involved in extinguishing a fire, during a year is usually much less than their stay in the exclusion zone.

To delay the spread of radioactive particles, water dispersed systems can be used, which act as a barrier and are not expensive. They are well studied at the present time and are widely used for the deposition of aerosols and particles of various genesis (Dushkin & Karpyshev, 2005; Vambol et al., 2018; Tsytsura & Starokozheva, 1999; Korytchenko et al., 2018; Vambol at al., 2019b). Liquid dispersed in the gas phase forms a fog, which prevents particles from moving further along their trajectory. These systems use for extinguishing fires, namely, improving the parameters of impulse fire extinguishing installations in terms of range and weight and size characteristics, which reduces the thermal radiation effect on the rescuer, which ensures the feasibility of using such installations for extinguishing large-scale fires (Korytchenko et al., 2018; Vambol, 2013); for spraying liquid, which increases the fire extinguishing efficiency by maintaining a predetermined pressure, which ensures the release of the entire extinguishing agent mass (Dushkin & Karpyshev, 2005); for create an obstacle in the form of a water wall, dome, etc. (Vambol, 2013). At the same time, a wide variety of engineering and technical devices are used to solve practical problems, such as a piston engine, an atomizer, various design configurations of nozzles, etc.

Researchers (Dvornik et al., 2018), through laboratory studies, came to the conclusion that forest fires insignificantly affect the health of fire-fighters directly involved in extinguishing. However, despite adequate methodology and good laboratory equipment, it should be noted that there were no direct measurements of air concentration or deposition after fire. This would be useful because the airborne radionuclide activity is highest near the source of ignition and transuranic elements (TUE) contribute to the total effective dose.

At the same time, the authors of (Azarov et al., 2015b), based on data (Table 2) on radioactive contamination of various objects and territories of the Chernobyl zone and operational control of radioactive air pollution during a forest fire in the CEZ by numerical modelling of their own mathematical model, obtained risks for fire-fighters during extinguishing forest fires (Table 4).

Table 4. Radiation risk from external (R_{int}) and internal (R_{inhal}) exposure to various radionuclides, obtained by calculation

Radionuclide	Radiation risk	
	R_{int}	R_{inhal}
^{137}Cs	$6,1 \cdot 10^{-4}$	$6,1 \cdot 10^{-4}$
^{90}Sr	$4,9 \cdot 10^{-3}$	$6,3 \cdot 10^{-4}$
^{238}Pu	$0,8 \cdot 10^{-3}$	$8,7 \cdot 10^{-4}$
$^{239,240}Pu$	$1,3 \cdot 10^{-4}$	$9,1 \cdot 10^{-3}$
^{241}Am	$5,3 \cdot 10^{-2}$	$3,5 \cdot 10^{-2}$

During the modelling, a significant number of factors were taken into account, such as the likelihood of serious damage to the fire-fighter's health from the received radiation dose; probability distribution of initiating events - the number of fires in the territories contaminated with radionuclides; the frequency of fires that lead to the release of radioactive combustion products; content of radionuclides in combustible materials; total activity of radionuclides released into the atmosphere; the expected time period between two fires; external radiation dose (due to inhalation of radioactive combustion products with air entering through the gastrointestinal tract and open wounds) and internal radiation dose (due to the influence of radionuclide radiation from a smoke cloud and a plume of radioactive combustion products falling onto the surface) and many others.

Table 4 shows that the radiation risk limit for a fire-fighter who is involved in extinguishing a fire in the Chernobyl zone may exceed the maximum individual radiation risk limit - 10^{-3} (NRBU, 2000), so special protection measures must be applied.

In work (Evangeliou & Eckhardt, 2020), when studying the real conditions for extinguishing a fire in April 2020 (Ukraine), which lasted 22 days, it is reported that even if fire-fighters remain in the CEZ after trying to extinguish fires, and then return to extinguish another fire the next day, remaining 60% of the time in indoors, the total doses will amount to about 1% of the annual external exposure dose from the background radiation left over from the Chernobyl accident. Nevertheless, even in such a situation, firefighters should be equipped with the necessary respiratory protection, and field hospitals should be organized in places where firefighters are located (Khan et al., 2019a; Khan et al., 2019b) for a quick response in case of deterioration of their health. These hospitals are also recommended to be equipped with inexpensive mobile filters that absorb toxic gases, for example based on composite films (Mozaffari et al., 2021).

Consequently, the problem of predicting the consequences of fires from radiation forests and protecting fire-fighters requires more detailed study.

As for the personnel of the exclusion zone who are not involved in extinguishing the fire, for them the inhalation component of the total dose (as well as external exposure from radionuclides) in the air does not matter (Yoschenko et al., 2006). This is explained by the fact that there is a sharp decrease in the concentration of transported radionuclides with distance from the source of release (Fig. 3, Yoschenko et al., 2006).

The consequences of forest fires in radiation-contaminated areas for the inhabitants of this region are also controversial. Therefore, the authors of (Evangeliou et al., 2014) made assessments of the impact of various scenarios of forest fires on public health (using a linear non-threshold model). In this case, all the main routes of exposure were taken into account, namely the presence in the polluted atmospheric cloud, deposition, inhalation of ^{137}Cs, ingestion (contribution of the presence of ^{137}Cs in food). The authors concluded that densely populated centres could be affected by fires in radioactive forests, especially in Central and Eastern Europe, due to the likely transfer of significant amounts of ^{137}Cs. Therefore, large fires in contaminated forests can be classified as “an accident with local or more severe consequences” or even as a “serious accident” according to the projected ^{137}Cs emissions (Evangeliou et al., 2014).

The most recent information on the impact on the population is presented in (Evangeliou & Eckhardt, 2020), where the radioactive situation that developed in April 2020 in the CEZ was studied. This document reports that for an adult in Kiev, Ukraine, the total effective dose was 2–5 μSv and minor doses (nSv) in Belarus, Russia and Europe. That is, no effect on the health of the local, regional or European population is expected, since all doses are radiologically insignificant.

5. Conclusions

Periodically occurring fires in radioactively contaminated forests force the development of scientific recommendations to improve the effectiveness of their prevention. This is most relevant for areas near populous cities, such as Kiev, since a large number of people fall under the influence of smog. For this purpose, the most effective detection methods should be studied and applied. For example, until 2018 in the CEZ on the Belarus territory there was no early warning system for the population of villages located among forest lands (Dvornik et al., 2018). Such systems do not implemented in Ukraine today also. The introduction of early detection systems would make it possible to prepare: (i) the population of villages to protect houses or provide them with knowledge about personal protective equipment that would help avoid additional doses; (ii) promptly take measures to extinguish the fire to so that it is not distributed (in this case, fire-fighters must be equipped with the necessary tools (Sokolov et al., 2018), effectively protected from thermal radiation (Ragimov et al., 2018; Su & Li, 2016) and radionuclides (Yamada et al., 2020); (iii) notify residents of large cities the need to use respiratory protection and not leave the buildings, if possible.

Moreover, in the future, an increase in temperature is expected in polluted forests, while the amount of precipitation will remain the same or slightly decrease. These changes have important implications for fire risk policy and fire management (Evangeliou et al., 2015). This indicates that the frequency of fires will increase due to dry days.

Considering the socio-economic situation in Ukraine, the introduction of early detection systems is the most profitable than the elimination of the consequences of such emergencies.

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