Interactive comment on “Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone” by Valery Kashparov et al.

Anonymous Referee #2 Received and published: 10 December 2017

The measurements presented in this paper constitute a very useful database from the accident of Chernobyl back in 1986. I am very supportive in open data policy, especially when refers to measurements of radionuclides. Personally, I have been chasing such measurements for a long time and I have sent many inquires to the IAEA and the JRC about the measurements of Cs137 that were used to create the ATLAS map, but I haven’t received any convincing answer about their fate.

I have minor comments on the manuscript and I strongly recommend it for publication once they are addressed.

- First, when reading the manuscript, I didn’t understand where this Ivankov region is. I needed to search on google in order to see where exactly this region is. I think it is essential to change Figure 3 and add a secondary map in the same figure where you "zoom out" the existing map and showing, for instance, a map of Ukraine highlighting the Ivankov region.

- Line 56: "to leads" —-> "to lead"

- Lines 71-78 are the same with the last couple of sentences in the Abstract. Please re-frase this part in the abstract of after line 71.

- You must link your database with the data that were published in 2016 by Evangeliou et al. (http://dx.doi.org/10.1016/j.envpol.2016.05.030) and stored in radio.nilu.no. They are supposed to be the most extended measurements of deposition over Europe since 1986. I went through the paper and downloaded the data presented there. More than 10 thousand measurements from 1986 are presented for Cs137, with about 30-40% in Ukraine, but much less for Cs134 (see Fig.1 and 2).

- In the aforementioned paper, there are some very dense measurements for Cs137, Sr90, Pu238, Pu239, Pu240 and Pu241 from the CEZ. I have plotted the data presented there in the attached figures (Fig.3-6). These are reported as decay corrected to 2015 and they were provided by the Ukrainian authorities. I think you need to state/prove somewhere whether or not the data you present here are not the same with these presented in the website radio.nilu.no.

- I think it is really important to link your measurements with the data in radio.nilu.no. If in the future someone ever tries to find similar measurements, it would help a lot if finding your paper can give additional information about other possible measurements.

Author response

Thank you for refereeing our paper. We respond to your suggestions in the following way (text in yellow) and by using ‘track changes’ in the paper below which has already been updated to reflect Referee 1 comments.

The measurements presented in this paper constitute a very useful database from the accident of Chernobyl back in 1986. I am very supportive in open data policy, especially when refers to measurements of radionuclides. Personally, I have been chasing such measurements for a long time and I have sent many inquires to the IAEA and the JRC about the measurements of Cs137 that were used to create the ATLAS map, but I haven’t received any convincing answer about their fate.

I have minor comments on the manuscript and I strongly recommend it for publication once they are addressed.

- First, when reading the manuscript, I didn't understand where this Ivankov region is. I needed to search on google in order to see where exactly this region is. I think it is essential to change Figure 3 and add a secondary map in the same figure where you "zoom out" the existing map and showing, for instance, a map of Ukraine highlighting the Ivankov region.

References to Ivankov consistently changed to Ivankov district and explained in text. Map figures updated with addition of Ivankov district or of Chernobyl exclusion zone.

- Line 56: "to leads" —-> "to lead" – text updated to say 'to lead'

- Lines 71-78 are the same with the last couple of sentences in the Abstract. Please rephrase this part in the abstract of after line 71. Abstract amended to remove repetition.

- You must link your database with the data that were published in 2016 by Evangeliou et al. (http://dx.doi.org/10.1016/j.envpol.2016.05.030) and stored in radio.nilu.no. They are supposed to be the most extended measurements of deposition over Europe since 1986. I went through the paper and downloaded the data presented there. More than 10 thousand measurements from 1986 are presented for Cs137, with about 30-40% in Ukraine, but much less for Cs134 (see Fig.1 and 2).

- In the aforementioned paper, there are some very dense measurements for Cs137, Sr90, Pu238, Pu239, Pu240 and Pu241 from the CEZ. I have plotted the data presented there in the attached figures (Fig.3-6). These are reported as decay corrected to 2015 and they were provided by the Ukrainian authorities. I think you need to state/prove somewhere whether or not the data you present here are not the same with these presented in the website radio.nilu.no.

- I think it is really important to link your measurements with the data in radio.nilu.no. If in the future someone ever tries to find similar measurements, it would help a lot if finding your paper can give additional information about other possible measurements.

I registered for http://radio.nilu.no and had a look at their restricted data for Chernobyl. The data differ to Kashparov et al. most notably because they were collected in 1986 and 2015. No data (apart from the hot particles dataset) are presented for 1986 or 2015 in our paper and accompanying dataset. We have added a table (in response to Referee 1 comments) to fully explain the data which outlines sampling years and analyses undertaken (Table 1.) We have added reference to the Evangeliou paper to the revised manuscript (Background section).

Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone

Valery Kashparov[1,3], Sviatoslav Levchuk[1], Marina Zhurba[1], Valentyn Protsak [1], Yuri Khomutinin[1], Nicholas Beresford[2] and Jacqueline Chaplow[2*].

[1]- Ukrainian Institute of Agricultural Radiology of National University of Life and Environmental Sciences of Ukraine, Mashinobudivnykiv str.7, Chabany, Kyiv region, 08162 Ukraine

[2]- NERC Centre for Ecology & Hydrology, CEH Lancaster, Lancaster Environment Centre, Library Av., Bailrigg, Lancaster, LA1 4AP, UK

[3]- CERAD CoE Environmental Radioactivity/Department of Environmental Sciences, Norwegian University of Life Sciences, 1432 Aas, Norway

[*]– Corresponding author (5)

Abstract. The data set "Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone" was developed to enable data collected between May 1986 (immediately after Chernobyl) and 2014 by the Ukrainian Institute of Agricultural Radiology (UIAR) after the Chernobyl accident to be made publicly available. The data set includes results from comprehensive soil sampling across the Chernobyl Exclusion Zone (CEZ). Analyses include radiocaesium (^{134}Cs and ^{134}Cs) ^{90}Sr, ^{154}Eu and soil property data, Plutonium-isotope activity concentrations in soil (including distribution in the soil profile), analyses of 'hot' (or fuel) particles from the CEZ (data from Poland and across Europe are also included) and results of monitoring in the Ivankov district, a region adjacent to the Exclusion Zone.

The purpose of this paper is to describe the available data and methodology used to obtain them. The data will be valuable to those conducting studies within the CEZ in a number of ways, for instance: (i) helping perform robust exposure estimates to wildlife; (ii) predicting comparative activity concentrations of different key radionuclides; (iii) providing a baseline against which future survey in the CEZ can be compared; (iv) as a source of information on the behaviour of fuel particles; (v) performing retrospective dose assessments; (vi) assessing natural background dose rates in the CEZ.

~~Recently, t~~The CEZ ~~was~~ has been proposed ~~suggested~~ as a 'Radioecological Observatory' (i.e., a site that will provide a focus for ~~joint,~~ long-term, radioecological collaborative international research to the future success of this concept ~~h~~is ~~to be successful~~open access to ~~, relevant~~ data for the CEZ are a first step in this process.

The data and supporting documentation are freely available from the Environmental Information Data Centre under the terms and conditions of the Open Government Licence: https://doi.org/10.5285/782ec845-2135-4698-8881-b38823e533bf.

1 Background

The accident in reactor number four at the Chernobyl nuclear power plant (ChNNP), Ukraine, on the 26th April 1986 remains the worst in the history of nuclear power generation. Starting on the 27th April the human population and farm animals were evacuated from an area of circa 3500 km^2 to create what has become known as the Chernobyl Exclusion Zone (CEZ). Subsequently, the area administered as the CEZ has increased to approximately 4760 km^2. The area of the CEZ in the Ukraine is approximately 2598 km^2, the remainder being in Belarus. The deposition of radionuclides over the CEZ is known to be highly spatially heterogeneous. Releases from the Chernobyl reactor occurred over a period of about ten days. There is a narrow band of high radioactivity to the west of the reactor (often referred to as the western trace) which represents deposition from the initial explosion (Figure 1). Higher levels of contamination to the north and to a lesser extent the south are ~~as~~ a consequence of releases over the days following the accident.

Figure 1. Spatial pattern of ^{90}Sr contamination (kBq m^{-2}) estimated for 1997 (UIAR, 1998)

The CEZ has many features making it an important radioecological study site:

- Contamination levels are such that the behaviour/transfer/mobility of a number of radionuclides can be studied (^{137}Cs, ^{90}Sr, ^{241}Am, Pu-isotopes, U-isotopes, ^{129}I, ^{14}C, ^{36}Cl and ^{99}Tc).
- The presence of radioactive particles means that their behaviour in the environment can be studied (Kashparov et al., 1999, Beresford et al., 2016). Fuel particles are weathered with time such that mobilisation of ^{90}Sr has been observed to lead~~s~~ to increased contamination of plants (Salbu et al., 1994, Oughton et al., 1993; Kashparov et al., 1999). Fuel particles were released in two different forms (Kashparov et al., 1996): Non-oxidized fuel particles of the initial release (26th April 1986), formed by the mechanical destruction of nuclear fuel. These first particles formed a 100 km long and up to 1 km wide path to the west of the plant, and oxidized fuel particles which were formed during the subsequent reactor fire (from 26th April to 5th May 1986) and deposited to the north and south of the plant.

- Dose rates remain sufficiently high that we may expect to observe effects on wildlife in some areas. Furthermore, published results on radiation effects from the CEZ are contentious with a lack of agreement on interpretation amongst scientists and a high public profile (Beresford and Copplestone, 2011).
- A wide range of terrestrial and aquatic species and habitats are present. The Ukrainian area, the focus of this paper, contains forests, abandoned farmlands, wetlands, flowing and standing waters, deserted villages and urban areas.

Recently, the CEZ was suggested as a 'Radioecological Observatory' (http://www.radioecology-exchange.org/content/radioecological-observatories; Steiner et al., 2013), i.e., a radioactively contaminated site that will provide a focus for joint, long-term, radioecological research which will help address challenges identified for the field of radioecology (Hinton et al., 2013). For this to be successful, relevant data for the CEZ need to be made openly available; indeed the deficiency of open data has been highlighted as one of the causes for the lack of scientific consensus with regard to published studies from within the CEZ and more recently areas affected by the 2011 Fukushima accident (Beresford et al., 2012; Barnett & Welch, 2016).

In this paper we describe a series of data sets focussed on radionuclide deposition and radioactive particles within and around the CEZ predominantly from studies conducted by the Ukrainian Institute of Agricultural Radiology (UIAR) (now part of the National University of Life and Environmental Sciences of Ukraine (NUBIP)). The accompanying data are freely available (https://doi.org/10.5285/782ec845-2135-4698-8881-b38823e533bf) under the terms of the open Government Licence. With respect to radioactive particles, data are also presented from samples collected in Poland in 1986.

The purpose of this paper is to describe the available data and methodology used to obtain them. The data will be valuable to those conducting studies within the CEZ in a number of ways, for instance: (i) helping perform robust exposure estimates to wildlife (Beaugelin-Seiller submitted); (ii) predicting comparative activity concentrations of different key radionuclides; (iii) providing a baseline against which future survey in the CEZ can be compared; (iv) as a source of information on the behaviour of fuel particles; (v) performing retrospective dose assessments; (vi) assessing natural background dose rates in the CEZ.

Whilst many of the results of the studies described have previously been used for various purposes within refereed or other publications (e.g. Kashparov et al., 2001, 2003, 2004, 2006; Zhurba et al., 2009) the complete underlying data sets have not previously been published. The dataset we

describe, resulting from detailed samplings in the Ukraine, add to the now openly available Chernobyl soil contamination/deposition data for wider areas of the former Soviet Union and Western Europe (Chaplow et al., 2015a,b; Evangeliou et al., 2016).

2 Data

There are six data sets available in Kashparov et al., 2017 and an overview of the contents of each is presented below and in Table 1:

1. Spatial data set of radiocaesium, ^{90}Sr and soil chemistry parameters resulting from a soil sampling exercise conducted during the summer of 1997. The data set comprises results from 1200 soil samples reporting ^{134}Cs, ^{137}Cs, ^{90}Sr and some ^{154}Eu activities in soil (kBq m^{-2}), some chemical parameters for soils (e.g. pH, exchangeable Cs, percentage humus), soil type at the sampling site and latitude-longitude co-ordinates. The data set also contains information for additional samples from some of the data sets below (e.g., this data set contains radionuclide activity in soil for all sampling though for some of these there are no corresponding soil chemistry data).
2. Pu isotope measurements in bulk soil samples reporting results for the analyses of ^{238}Pu and ^{239,240}Pu on a subset of 82 of the samples from the above data set and an additional twelve samples collected from within the CEZ and outside it to a distance of 200 km between 2000 and 2001.
3. Pu isotope measurements in sectioned soil samples reporting results from cores sectioned at different depths collected at nine of the 12 sites sampled between 2000 and 2001.
4. 'Hot' or fuel particle data set presenting radionuclide activity and some physical characteristics of: (i) 1380 'hot particles' (predominantly fuel particles) extracted from soils collected in the CEZ (largely from in the inner 10 km zone) over the period 1987 to 2000; (ii) 206 particles collected from north-east and Warsaw area (Poland) in September 1986 (data courtesy of Warsaw University (Dabrowska et al., 1988, Osuch et al., 1989); (iii) 294 particles collected from within the 'Shelter' (or sarcophagus) in 1992; (iv) data from published literature on particles collected in different European countries between 1986 and 1987.
5. Fuel particle dissolution data set presents results from studies on 115 soil samples, collected within the CEZ between 1995 and 1997, to determine the proportion of undissolved fuel particles.
6. Ivankov ~~region~~ district data presents unreported data of a survey of the Ivankiv Raion, ~~Ivankov~~ a district in the Kiev Oblast~~region,~~ immediately to the south of the CEZ, conducted in 2014. The

Ivankov district borders the CEZ and Ivankov, the administrative centre is situated ~80 kilometres from Kiev and ~50 kilometres from Chernobyl NPP. The data set contains dose rates measured at approximately 3400 sites across the Ivankov ~~region~~ district and activity concentrations of ^{90}Sr, ^{137}Cs and natural series gamma-emitting radionuclides in 547 soil samples sampled in 2014.

The above numbers are used in Table 1 and subsequently to identify the data sets.

Table 1. A description of the data presented in this paper and available from Kashparov et al., 2017.

Locations of sampling for studies 1, 2, 3, and 5 are presented in Figure 2 and those for the Ivankov ~~region~~ district are shown in Figure 3 (below). Reported activity concentrations for all data sets discussed are presented for the date of measurement which is provided in the accompanying data sets.

Figure 2. Sampling locations for the different studies in the CEZ (red – 1.Spatial data set of radiocaesium, ^{90}Sr and soil chemistry parameters; - dark blue – 2.Pu isotope measurements in bulk soil samples; yellow - 3.Pu isotope measurements in sectioned soil samples; green - 5. Fuel particle dissolution data set; 6. Ivankov district (sampling locations see Figure 3.)

2.1. Overview of studies and available data

2.1.1 Spatial data set of radiocaesium, ^{90}Sr and soil chemistry parameters

Soil sampling

Soil samples were collected at about 1200 sites in the Ukranian CEZ in an area of 36 km radius around ChNPP between July 1995 and September 1997. Sites were selected using a grid and the approximate distance between sampling sites was about 1.2 km. For the narrow western (fuel particle) trace of the radioactive release, where contamination is characterised by a high gradient, the distance between the sampling sites was reduced to 100 to 500 m. Because of the large area of the CEZ, the majority of the sampling was conducted using a helicopter to rapidly move between sites; to sample forest areas motor vehicles were used for transport.

At each sampling point, the absorbed dose rate at a height of 1 m above ground surface was measured. Before soil sampling the homogeneity of the site (100 x 100m) was evaluated by measurement of absorbed dose rate at several points using a DRG-01T dosimeter ("Mekhanichesky zavod" (Mechanical Plant), Russia).

A composite soil sample was collected that consisted of five sub-samples of cores of 37 mm diameter, taken in the corners and in the centre of 2 to 5 m^2 to 30 cm depth (this approach is referred to as the 'envelope method' and is conducted in accordance to what is now to SOU 74.14-37-425:2006). SOU refers to the standard of the Ministry of Agrarian Policy and Food of Ukraine (industry standard of Ukraine). This approach was developed to obtain a representative soil sample (Khomutinin et al., 2001). The total mass was not less than 2 kg for the five cores. The sampling depth of 30 cm was chosen because it had been shown that ten years after the accident about 95% of the ^{90}Sr activity is associated with the upper 10 to 20 cm layer (Ivanov et al., 1997). To test that the sampling depth was adequate the vertical distribution of ^{90}Sr in sandy soil profiles (up to 1 m depth) was determined and the ^{90}Sr:^{154}Eu activity ratio in the samples was measured. Fuel particles have a characteristic ^{90}Sr:^{154}Eu; if this ratio deviates from that expected it is indicative of ^{90}Sr being leached down the profile. In most of the cores more that 95% of the ^{90}Sr was located in the upper 30 cm layer. Only in a few sites (less than 0.1% of all sites) with a low organic matter content was there a significant percentage of ^{90}Sr (>20%) that had migrated deeper than 30 cm (Shestopalov et al., 2003).

The co-ordinates of the sampling sites were determined by means of a GPS-receiver (ScoutMaster) using the WGS-84 (World) system. In order to estimate the accuracy of the co-ordinates and their correspondence to the topographic basis, GPS measurements were performed at several points with known co-ordinates. It was shown that the accuracy of the GPS-receiver was about 100 m with a systematic deviation of about 300 m.

The same methodology was used for estimating radionuclide activity concentrations in the other data described below unless otherwise indicated.

Soil activity measurements

The collected soil samples were dried, sieved through a 1 mm sieve and homogenized. Four sub-samples were taken from each sample for the determination of the total contents of radionuclides: three sub-samples of 100 cm^3 volume and one of 1000 cm^3 volume for the measurement of gamma emitting radionuclides in a Marinelli container. Measurements of gamma emitting radionuclide contents were performed on all four sub-samples (C_i, Bq kg^{-1}) using gamma-spectrometry. If the relative difference of the sub-sample measurements $(C_{max}-C_{min})/(C_{max}+C_{min})$ exceeded 0.15 for the ^{137}Cs activity concentrations, the sub-samples were bulked and remixed. The resultant sample was again divided into replicates which were re-analysed. Once $(C_{max}-C_{min})/(C_{max}+C_{min})$ was <0.15, a 100 cm^3 sub-samples with an approximate average ^{137}Cs activity concentration was chosen for the measurement of the ^{90}Sr specific activity. This procedure was followed to ensure that the sub-sample analysed for ^{90}Sr was representative of the sample as a whole.

Gamma spectrometry measurements were performed using HPGe-detectors, of 30 % relative efficiency and 1.90 keV FWHM for 1333 keV (GEM-30185, EG&G ORTEC, USA) and a multichannel analyser (ADCAM-300, ORTEC, USA) using GammaVision32 software. The efficiency calibration was carried out for the 1 L Marinelli geometry using a spiked soil sample containing ^{241}Am, ^{243}Am, ^{152}Eu, ^{154}Eu, ^{137}Cs, ^{40}K. The average counting time was about 1 hour; for samples of lower activity the counting time was extended to obtain an acceptable error on the measurement (<30 % at 95th percentile confidence interval).

The activity of ^{90}Sr was determined using a radiochemical method (Pavlotskaya, 1997) with treatment of the samples by boiling in 6M nitric acid for four hours. This method was used to dissolve as much of the fuel particles as possible (Kashparov et al., 2003); it has been estimated that for particles collected from the western trace within 5 to 10 km of the ChNPP this method may underestimate ^{90}Sr activity by up to 20 % (Kashparov et al., 2004). After filtration of the solution, hydroxides of high-valence metals (Fe, Al, Ti, Mn, Th, U) were extracted by adding ammonia into the solution. After acidification, the solution was left for three weeks to reach equilibrium between ^{90}Sr and ^{90}Y. Subsequently, stable Y was added to the solution and Y precipitated by addition of ammonia. The precipitate was incinerated to yield Y_2O_3 and after one day (to allow the decay or radium daughters) ^{90}Sr was measured using a low-background beta-counter (CANBERRA-2400, USA). The radiochemical procedure removed ^{137}Cs from the sample which increased the accuracy of the subsequent ^{154}Eu gamma-spectrometric measurements to determine the ^{90}Sr:^{154}Eu ratio (gamma counting to determine the ^{154}Eu activity was conducted after extraction of high-valence metals).

Determination of the main agrochemical characteristics

Standard methods were used to determine humus content (which equates to organic matter content) (GOST 26213-91), pH_{H2O} (GOST 26423-85), pH_{Kcl} (GOST 26483-85), hydrolytic acidity (determined using the Kappen method (GOST 26212-91)), exchangeable Ca (GOST 26487-85), exchangeable K and P contents were determined using a method appropriate to the specific soil type (GOST 26207-91, GOST26204-91). GOST refers to the National Standard of USSR and Ukraine prior to the break-up of the Soviet Union in 1991.

Mechanical composition (i.e. percent clay, percent silt, sand) were determined on the soils but not reported in the data. Instead, they have been used to attribute soils to the USSR classification system. Table 2 presents soil types in the CEZ described using USSR ~~countries~~ classification and in accordance with the FAO/UNESCO system (Stolbovoi, 2000). The soil type at each sampling site was attributed to one of these codes and this is presented within the data.

Codes 116 to 143 in the data were sampled from around the village of Bober which was not within the CEZ but at which high deposition values were found. No agrochemical measurements were made at these sites except pH.

Table 2. Soil classifications appropriate to the CEZ.

2.1.2 Pu isotope measurements

From the data set described above 82 samples from sites along the main traces of the release were selected for analysis of Pu-isotopes. For determination of plutonium radioisotopes at a given site, one of the homogenized 100 cm^3 samples was used. After heating at 450 °C overnight, the samples were boiled for 4 hours in 6M HNO_3. Plutonium radioisotopes were extracted by a standard radiochemical method (Pavlotskaya, 1997). Chemical yield was calculated using ^{236}Pu or ^{242}Pu as tracers. Plutonium was extracted from the resultant solution using ion-exchange resin (VP-1AP, Russia). After elution and evaporation plutonium was extracted by electrical deposition onto stainless steel plates. Activities on the plates were measured using a Soloist alpha-spectrometer equipped with a Soloist-U0300 detector (EG&G ORTEC, USA).

An additional set of 12 samples were collected in autumn 2000 and analysed to determine Pu-isotopes using the same methodology. These samples were collected at distances of up to 200 km outside of the CEZ in westerly, southerly and easterly directions.

2.1.3 Pu isotope measurements at different depths

Apart from having total Pu isotopes determined as above for the bulked soil sample, cores from eight of these sampling sites were sectioned into layers (0 to 2, 2 to 4, 4 to 6, 6 to 8, 8 to 10, 10 to 15, 15 to 20, 20 to 25 and 25 to 30 cm) and analysed for Pu-isotopes, ^{137}Cs and ^{90}Sr.

A further site close to Pripyat was sampled in 2001 to a depth of 110 cm and the core was sectioned into 10 cm slices (these are identified as 1_J_w in the accompanying data sets). Each of these depth samples was analysed to determine ^{238}Pu, $^{239,240}Pu$, ^{137}Cs and ^{90}Sr as described above.

2.1.4 'Hot' or fuel particles

The initial explosion in the Chernobyl reactor released a large ~~numbers~~ amount of uranium dioxide fuel particles with a median radius of 2-3 µm which were deposited in a narrow band up to 100 km to the west of the ChNPP (Kashprov et al., 1999). The explosion also released relatively large fuel fragments ranging from 10's to 100's µm in size. These larger fragments were ~~largely~~ predominantly deposited ~~within~~ at a distance of 2-5 km ~~of~~ from the reactor (Kashparov et al., 1999). The deposition

of particles was a distinguishing feature of radioactive contamination of the Chernobyl accident and the behaviour of radionuclides associated with such particles in the environment had not previously been considered (Loshchilov et al., 1991, Beresford et al., 2016).

In 1987, the State Committee of Hydrometeorology of the USSR and the Scientific Centre of the Defence Ministry of the USSR created a regular sampling network in the CEZ (Loshchilov et al., 1991). Fifteen points were chosen on each of 36 transects defined at 10° intervals within 60km of the ChNPP. Soil samples were collected during 1987 and 1989 at each point, except for those located in woods, rivers and lakes; the majority of sampling sites were located within the inner 10 km of the CEZ. The samples (15 cm in diameter and 5 cm deep) were measured in Marinelli beakers using a high-purity Ge detector. From a subset of these samples, all collected within the 30 km zone, more than 1,200 relatively large (size >10 μm) hot particles (activity >100 Bq) were identified and isolated by scanning thin soil layers with a dosimeter (Kuriny et al., 1993). In some instances more than one particle was extracted from the same soil sample (in the data the identifier code starts with the same number).

About 500 additional 'hot' or fuel particles were collected in a similar manner from soils sampled using the same approach in the CEZ during the period 1989–1996 (Kashparov, 2003).

In the inner zone of the CEZ, where these samples were collected, up to 97% of particles comprised finely-dispersed nuclear fuel particles. The other 3% were what are known as 'ruthenium' or condensed particles, a matrix of iron group elements with a high content of ^{103,106}Ru (Kashparov et al., 1996). Condensed particles were formed when highly volatile radionuclides released from the fuel matrix were condensed onto particles of dust, construction materials etc. (Kashparov et al., 1996). Within the database the type of each particle is identified as 'fuel' or 'condensed'.

The specific activity of the fuel particles corresponded to the activity of the fuel at the moment of the accident, excluding the volatile and highly mobile radionuclides such as ^{134,137}Cs and ^{103,106}Ru (Kuriny et al., 1993, Kashparov, 2003). The presence of fissionable material in the particles was demonstrated using neutron-activation analysis, electron probe microanalysis, and laser mass-spectrometry. Particle enrichment with ^{235}U was found to be about 1 to 2% (Kashparov et al., 1996); natural uranium consists of approximately 0.7% ^{235}U (USNRC, 2017). Particle size and radionuclide activity were measured by optical microscopy and by α-, β-, γ-spectrometry respectively. Gamma spectrometry was conducted using high purity germanium detector (GEM-30185, EG&G ORTEC, USA) of about 30% efficiency and 1.85 keV energy resolution (for ^{60}Co, 1332 keV γ-rays) connected to a multichannel analyser (ADCAM™ MCA 350, EG&G ORTEC, USA). Alpha spectrometry was conducted using a gold-silicon detector (DKP-

125-IA) linked to a SES-13 spectrometer. Following radiochemical separation using the methodology described above ^{90}Sr activity was determined using an α-β detector (CANBERRA-2400, USA).

An additional set of 294 particles were obtained from inside of the "Shelter" (or sarcophagus) in the reactor hall of the Chernobyl No4 unit early in 1992 and analysed as described above.

Using the ^{137}Cs and ^{90}Sr results for the particles, Kashparov (2003) estimated the effective duration and temperature for fuel particle annealing to be ~3.5 seconds at 2400 K respectively for particles of >10 µm from Western Trace. This confirmed an explosion-like mechanism of fuel particle formation during the accident (Kashparov, 2003).

For particles collected in the CEZ the data set presents 'burn-up' values. Burn-up is used to describe the fraction of fuel atoms having undergone fission. The burn-up distribution of fuel particles larger than 10 µm collected from the CEZ indicated that, at the moment of the accident, particles were released from the less irradiated ('younger') part of the reactor core. Burn-up values were lower in these particles (9.8 to 11 MW day kg^{-1}) in comparison with the estimated most probable fuel burn-up value of 14 MW day kg^{-1} in the 4^{th} unit of the ChNPP (Kuriny et al., 1993, Kashparov et al., 1996, Begichev et al., 1990; Kashparov et al., 1997). Table 3 presents estimated radionuclide activity concentrations at the time of the accident in fuel with different burn-up values. The lower burn-up of fuel contributing to particles within the CEZ resulted in particles with less radioactivity than if deposited particles had been largely formed from 'older' fuel in the reactor.

The data set also contains information on 206 particles collected from five areas in the north east of Poland. Particles were collected in autumn 1986 from wasteland and forest clearings; the total area sampled was approximately 6000 square metres (the data are supplied courtesy of Warsaw University; see Dabrowska et al., 1988 and Osuch et al., 1989 for methodology). In contrast to the CEZ, >40% of the particles collected in Poland were of the condensed form; the results for the Polish particles were decay corrected to the day of the accident. The Polish particles were divided into three forms A, B and C. Group A contained mostly ^{103}Ru and ^{106}Ru isotopes, group B particles were rich in other nuclides from the fission product spectrum and group C resembled group B particles in isotope contents but with a higher abundance of ruthenium.

For completeness and comparison, we have augmented the data with values from the published literature which present information on particles from: Bialystok in the Masurian Lakes region of northeast Poland (nine particles collected in November 1987) (Schubert and Behrend, 1987); Budapest, Hungary (15 particles collected in July 1986) (Balashazy et al., 1988); Stockholm, Gotland and Gavle in Sweden (41 particles collected in 1987) (Kerekes et al., 1991); Sofia, Bulgaria (five

particles) (Mandjoukov et al., 1992). Most of the particles from these studies were also 'ruthenium' condensation particles. Particles were selected in 1986 and activities were decay corrected to the time of the accident.

2.1.5 Fuel particle dissolution data set

Soil Sampling and preparation

Between July 1995 and May 1997, 115 soil samples were collected from sites within the CEZ at varying directions and distances from the ChNPP in order to reflect the variability of the physical and chemical characteristics of the fuel particles deposited (Kashparov et al., 1996, 1999, 2004). The sampling was carried out along the narrow western trace of fallout of the non-oxidized fuel particles of the first release (Chernobyl releases occurred over a period of 10 days (Smith & Beresford, 2005)) and at the southern and northern fuel traces of fallout of oxidized fuel particles (FP). At all sample sites, soddy podzolic sandy soils (type 2 from Table 2) were sampled. Where possible at each site, additional samples were collected from an area of peat soil within a radius of 300 m. It was assumed that within this area the deposited particles would be relatively similar, allowing the effect of soil type on particle behaviour to be studied. Density of contamination by ^{90}Sr varied at the sampling sites from 12 kBq m^{-2} to 60 MBq m^{-2}.

Two soil cores were collected at each sampling point: one sample was collected to a depth of 5 cm and 14 cm diameter; the second was taken to a depth of 30 cm with a 6 cm diameter. The 0 to 5 cm samples (containing the fuel particles) were used to determine soil pH_{H_2O} using the same method as above.

Strontium-85 and ^{90}Sr activity concentrations were determined on the 0 to 30 cm samples which were also used to estimate the fraction of remaining undissolved fuel particles. Soil samples were air-dried (approximately 25 °C), passed through a 1 mm mesh sieve and homogenised prior to analysis.

Estimation of remaining fraction of fuel particles

The fuel particle component in the soil samples was estimated from the fraction of exchangeable ^{90}Sr determined using a 2M NH_4Ac extraction with ^{85}Sr yield monitor (Kashparov et al., 1999). Three or four sub-samples of 100 cm^3 were taken from each 0 to 30 cm soil sample, and 5 ml of ^{85}Sr solution (activity of about 100 Bq) and 25 ml of water were added to each. After 6 to 48 days, the soil was subjected to extraction using 2 M NH_4Ac (solid: liquid ratio 1:10). The soil-extract solution was shaken for 1 hour and left for 1 day. Extractants and soil residues were separated by filtration, and the fraction of radiostrontium was determined in both the solution (A_{sol}) and the residue (A_{res}). The gamma

emitting radionuclides ^{137}Cs, ^{154}Eu, ^{241}Am and ^{85}Sr were measured using gamma spectrometry and ^{90}Sr by beta counting after radiochemical separation using the approach outlined above.

The percentages of ^{85}Sr and ^{90}Sr leached from soil (Δ^{90}Sr and Δ^{85}Sr respectively) were calculated as follows:

$$\Delta^{85}\mathrm{Sr} = \left\{\frac{A_{\mathrm{sol}}(^{85}\mathrm{Sr})}{A_{\mathrm{sol}}(^{85}\mathrm{Sr}) + A_{\mathrm{res}}(^{85}\mathrm{Sr})}\right\} \times 100\%$$

$$\Delta^{90}\mathrm{Sr} = \left\{\frac{A_{\mathrm{sol}}(^{90}\mathrm{Sr})}{A_{\mathrm{sol}}(^{90}\mathrm{Sr}) + A_{\mathrm{res}}(^{90}\mathrm{Sr})}\right\} \times 100\%$$

These percentages were used to calculate the fraction of undissolved fuel particles (ΔFP), estimated as:

$$\Delta FP = \left[1 - \frac{\Delta^{90}\mathrm{Sr}}{\Delta^{85}\mathrm{Sr}}\right]$$

For samples with a low ^{90}Sr:^{154}Eu ratio, it had previously been shown that leached ^{90}Sr had been removed from the 0 to 30 cm layer (Kashparov et al., 1999). This migration was particularly significant for sandy soils with very low humus content. Here, for such samples, the total estimated ^{90}Sr content was used to assess the fraction of undissolved fuel particles rather than $A_{res}(^{90}Sr)$. The total ^{90}Sr content was derived from the vertical distribution of ^{90}Sr and ^{154}Eu activity. From estimates of initial activity concentrations in the fuel the ^{90}Sr:^{154}Eu ratio in 1996 of 56 would be expected (see discussion of predicted activity levels in fuel presented below).

The data contains a limited number of negative values which are the consequence of a low percentage of ^{90}Sr in the exchangeable form and a high associated error. Users of the data should assume these values to be zero.

Table 3. The activity concentrations of radionuclides in the ChNPP 4th unit nuclear fuel with different burn-up, Bq g^{-1}.

2.1.6 Survey of the Ivankov district

Three thousand three hundred and eighty nine sampling points were identified for survey in 2014, using a 1 km grid placed over the Ivankov ~~region~~ district and surrounding 3 km (Figure 3) (Kashparov et al., 2014). The co-ordinates of the sampling sites were determined by means of a GPS-receiver (Garmin, GPSmap 78S) using the WGS-84 (World) system with the accuracy of 10 m or less.

Measurements of ambient equivalent dose rate (hereafter referred to as dose rate) were carried out at heights of 1 m and 0.1 m above ground surface at 1 km intervals using this grid. Equivalent dose was measured using certified gamma-beta-irradiation dosimeters (RKS-01, Stora-TU, Ukraine). The measurement range of the dosimeters was approximately 0.1 to 1000 μSv hr^{-1} and the time taken to obtain a statistically reliable estimate was approximately 20 s. Seven of the sites selected for survey were inaccessible however the locations have been left in the data for completeness.

An estimation of 'zero background' for the dosimeters was made by taking measurements over a frozen water body in the centre of the Ivankov ~~region~~district. The contribution of gamma irradiation from natural and anthropogenic radionuclides was seen to be negligible and hence the readings were the sum of cosmic radiation and the detectors own background (Kashparov et al., 2014). The background dose rate of the devices themselves were determined in the laboratory by taking measurements within a lead shielded (10 cm thick) area. Background dose rate of the detectors was estimated to be 0.05 μSv h^{-1} and the 'zero background' determined over the frozen lake was 0.08 μSv h^{-1}. Therefore, the contribution of cosmic radiation in the study area can be estimated to be approximately 0.03 μSv h^{-1}. Contributions from cosmic and instrument background were subtracted from measured values reported in the data set.

Figure 3. Map of the soil sampling locations in the Ivankov district which borders the CEZ: soil sampling and gamma survey (red stars); gamma survey only (grey circles).

Five hundred and forty seven soil samples were collected. Sampling locations were every third dose rate measurement point apart from within settlements where soils were sampled at every measurement point. Sample sites were selected that were undisturbed, relatively flat, with consistent vegetation cover, and where dose rate estimates did not vary by more than 30%. Samples were taken at a distance from the nearest buildings or trees which equated to two times the height of the buildings or trees. The exception was for samples collected from forest or scrubland where the sample site was positioned equidistantly from the nearest trees or shrubs. Sampling points were located no closer than 20 m to roads or places where accumulation or wash-off of radioactive contamination was possible.

The envelope method was used to collect soil samples using a 37 mm corer down to a depth of not less than 20 cm. The mass was not less than 3 kg for the composite sample.

Soil samples were oven dried at 105°C to constant weight, homogenized and sieved through a 1 mm sieve. Sub-samples of 100 to 150 g were taken for ^{90}Sr analysis and for gamma analysis a 1 L Marinelli container was filled.

The approach used to determine ^{90}Sr activity concentration in soil samples was based on the standard ISO 18589-5:2009 (ISO2009). Strontium-90 activity was estimated through measurement of its daughter product, ^{90}Y. The radiochemical preparation involved digestion of the ashed sample in 8M HNO_3 followed by oxalate precipitation. Strontium was purified using ammonia and saturated sodium carbonate solution. The resultant strontium carbonate was dissolved in 2.5M HNO_3, Y carrier was added and stored for 2 weeks such that ^{90}Y reached equilibrium. Yttrium was then precipitated as oxalate and ^{90}Y was measured using a beta-spectrometer (SEB-70, AKP, Ukraine). The radiochemical separation yield was calculated using carriers such as stable Sr and Y measured using atomic absorption spectroscopy (Varian). Gamma analyses were conducted as described above. Quality assurance of radioanalytical procedures was based on ISO/IEC 17025 standards. The laboratory regularly participated in international and national proficiency tests (e.g. International Atomic Energy Agency).

The data set reports activity concentrations for the natural radionuclides ^{40}K, ^{226}Ra and ^{232}Th in addition to ^{137}Cs and ^{90}Sr. The mean activity concentrations for these radionuclides were 140 Bq kg^{-1} ^{40}K, at 12 Bq kg^{-1} ^{226}Ra and 10 Bq kg^{-1} ^{232}Th. Natural background radionuclides are sometimes cited as being relatively low in the CEZ (Møller & Mousseau, 2011) though there are few data in the International literature. On the basis of soil types we could expect the CEZ to have similar natural radionuclide activity concentrations in soils as the Ivankov ~~region~~district. These activity concentrations do appear to be relatively low compared to average values for e.g., the UK (Beresford et al., 2008).

Caesium-137 activity concentrations in the Ivankov ~~region~~ district soils range from 6 to 390 Bq kg^{-1} dry matter. Strontium-90 concentrations range from 1 to 160 Bq kg^{-1} dry matter. These compare to anticipated global fallout values of approximately 4 Bq kg^{-1} ^{137}Cs and 1 Bq kg^{-1} ^{90}Sr. Activity concentrations of both ^{137}Cs and ^{90}Sr were highest in the east of the Ivankov district (Figure 4). On an aerial basis ^{137}Cs ranged from 2 to 140 kBq m^{-2} and ^{90}Sr <1 to 60 kBq m^{-2}. The ^{137}Cs:^{90}Sr ratio increased to the west and south of the Ivankov ~~region~~ district with distance from the ChNPP (Figure 5.)

Dose rates at 1 m across the Ivankov ~~region~~ district ranged from 0.1 to 0.24 μSv h^{-1}. From natural radionuclides in soil and using conversion coefficients by UNSCEAR (1977), a dose rate of 0.01 to 0.07 μSv h^{-1} was estimated. There was a tendency for dose rates to increase with increasing ^{137}Cs activity concentration in soils although correlation was poor (R^2=0.11 for measurements at 1 m).

Figure 4. Spatial variation in ^{137}Cs (top) and ^{90}Sr (bottom) soil concentrations (kBq m^{-2}) in the Ivankov district in 2014~~5~~.

Figure 5. Spatial variation in 137Cs:90Sr ratio in the Ivankov ~~region~~ district (sampling points black stars).

3. Access and conditions of use.

All samples after gamma-spectrometry measurements are stored at NUBIP and can be made available on request.

The data described here have a Digital Object Identifier (doi:10.5285/782ec845-2135-4698-8881-b38823e533bf) and are freely available for registered users from the NERC-Environmental Information Data Centre (http://eidc.ceh.ac.uk/) under the terms of the Open Government Licence. The data must be fully referenced for every use as: Kashparov V., Levchuk S., Zhurba M., Protsak V., Khomutinin Yu., Beresford N.A. and Chaplow J.S. (2017): Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone. NERC-Environmental Information Data Centre doi:10.5285/782ec845-2135-4698-8881-b38823e533bf. Supporting documentation to aid in the reuse of this data is also available from the EIDC.

Acknowledgements

Funding for preparing this paper and accompany data set (Kashparov et al., 2017) was provided by the EU COMET project (http://www.radioecology-exchange.org/content/comet) and TREE (http://www.ceh.ac.uk/tree) project funded by the NERC, Environment Agency and Radioactive Waste Management Ltd. under the RATE programme.

References

Antonetz, A. V., Babich, A. A., Bayljuk, A. A., Barjakhtar, V. G., Kukhar, V. P., Los, I. P., Poyarkov, V. A., Kholosha, and Shestopalov, V. M.: Generalised evaluation of the risks resulted by the ChNPP accident. STCU, UREC, Kiev, Ukraine. (In Russian), 1998.

Arinushkina, E.V.: Guidebook on chemical analysis of soils. Moscow University Publishers, Moscow, Russia. (In Russian), 1961.

Arkhipov, N. P., Arkhipov, A. N., Voitsekhovich, O. V., Gladkov, G. N., Djepo, S. P., Drapeco, G. F., Kuchma, N. O., Korotkov, V. T., Lebega, V. S., Marchenko, V. I., Nosovsky, A. V., Sukhoruchkin, A. K., Tepikin, V. E., Tikhanov, E. K. and Shestopalov, V. M.: Bulletin of ecological situation in the Exclusion zone for first half-year of 1995. Issue 5, Chernobyl, Ukraine (In Russian), 1995.

Aronov, V.I.: Methods of creation of maps of geological and geophysical characteristics and application of geometry for mapping of oil and gas deposits using computers. Book Company "Nedra", Moscow, Russia (In Russian), 1990.

Arutyunyan R.V., Bolshov L.A., Borovoi A.A., Velikhov E.P. and Klyuchnikov A. A. Nuclear fuel in the Shelter of the Chernobyl NPP. Nauka Publishers, Moscow, Russia, (In Russian), 2010.

Balashazy, I., Hofm ann, W. and Martonen, T. B.: A model of particle deposition at airway bifurcations, J. Aerosol Med. 1, 190-191, 1988.

Barnett, C. and Welch, S.: Thirty years after the Chernobyl accident: what do we know about the effects of radiation on the environment? http://www.radioecology-exchange.org/sites/www.radioecology-exchange.org/files/files/Deliverable_56_COMET_workshop_4_final.pdf (last access 13 June 2017), 2016.

Beaugelin-Seiller, K., Garnier-Laplace, J. and Beresford, N. A.: Estimating radiological exposure of wildlife in the field, submitted Journal of Environmental radioactivity.

Begichev S. N., Borovoy A. A., Burlakov E. V., Havrilov S. L., Dovbenko A. A., Levina L. A., Markushev D. M., Marchenko A. E., Stroganov A. A., Tataurov A. K.: Preprint IAE-5268/3: Reactor Fuel of Unit 4 of the Chernobyl NPP (a brief handbook). Moscow. Publisher Kurchatov Institute of atomic energy, 21p. (In Russian), 1990.

Beresford, N. A., Barnett, C. L., Jones, D. G., Wood, M. D., Appleton, J. D., Breward, N. and Copplestone, D.: Background exposure rates of terrestrial wildlife in England and Wales. Journal of Environmental Radioactivity, 99, 1430-1439, doi:10.1016/j.jenvrad.2008.03.003, 2008.

Beresford, N. A. and Copplestone, D.: Effects of ionizing radiation on wildlife: what knowledge have we gained between the Chernobyl and Fukushima accidents? Integrated Environmental Assessment and Management, 7 (3). 371-373. Doi:10.1002/ieam.238, 2011.

Beresford, N. A., Barnett, C. L., Howard, B. J., Howard, D. C., Wells, C., Tyler, A. N., Bradley, S. and Copplestone, D..: Observations of Fukushima fallout in Great Britain, Journal of Environmental Radioactivity, 114. 48-53. Doi:10.1016/j.jenvrad.2011.12.008, 2012.

Beresford, N.A., Adam-Guillermin, C., Bonzom, J.-M ., Garnier-Laplace, J., Hinton, T., Lecomte, C., Copplestone, D., Della Vedova, C., Ritz, C.: Response to authors' reply regarding "Abundance of birds in Fukushima as judged from Chernobyl" by Møller et al.,~~ (~~2012~~)~~. Environmental Pollution 169, 139-140. http://dx.doi.org/10.1016/j.envpol.2012.05.013, 2012

Beresford, N. A., Fesenko, S., Konoplev, A., Smith, J. T., Skuterud, L. and Voigt, G.: Thirty years after the Chernobyl accident, J. Environ. Radioact., 157, pp. 38–40, doi:10.1016/j.jenvrad.2016.01.023, 2016.

Bunzl, K.: Probability for detecting hot particles in environmental samples by sample splitting, Analyst, 122, 653-656, 1997.

Chaplow, J. S., Beresford, N. A. and Barnett, C. L. Post Chernobyl surveys of radiocaesium in soil, vegetation, wildlife and fungi in Great Britain. NERC Environmental Information Data Centre. https://doi.org/10.5285/d0a6a8bf-68f0-4935-8b43-4e597c3bf251, 2015a.

Chaplow, J. S., Beresford, N. A., and Barnett, C. L.: Post-Chernobyl surveys of radiocaesium in soil, vegetation, wildlife and fungi in Great Britain, Earth System Science Data, 7, 215-221, https://doi.org/10.5194/essd-7-215-2015, 2015b.

Dabrowska, M., Jaracz, P., Jastrzebski, J., Kaczanowski, J., Mirowski, S., Osuch, S., Piasecki, E., Pienkowski, L., Szeflinska, G., Szeflinski, Z., Tropilo, J. and Wilhlemi, Z.: Isotopic composition of hot particles collected in North-East Poland. International Workshop on Hot Particles in the Chernobyl Fallout, October 28-29, Theuern, Germany, 1987.

David, M.: Geostatistical methods for assessment of stores of ore. Book Company "Nedra", Leningrad, Russia (In Russian), 1980.

Evangeliou, N., Hamburger T., Talerko N., Zibtsev S., Bondar Y., Stohl A., Balkanski Y., Mousseau T. A. and Møller A. P. Reconstructing the Chernobyl Nuclear Power Plant (CNPP) accident 30 years after. A unique database of air concentration and deposition measurements over Europe, Environmental Pollution, 216, 408-418, 2016.

Gedroits, K. K.: Chemical analysis of soils, Israel Program for Scientific Translations, Jerusalem, 1963.

GOST 26213-91 http://docs.cntd.ru/document/gost-26213-91 (last access: 16 May 2017)

GOST 26207-91 http://docs.cntd.ru/document/gost-26207-91 (last access: 16 May 2017)

GOST 26212-91 http://docs.cntd.ru/document/gost-26212-91 (last access: 16 May 2017)
GOST 26423-85 http://docs.cntd.ru/document/gost-26423-85 (last access: 16 May 2017)
GOST 26483-85 http://docs.cntd.ru/document/gost-26483-85 (last access: 16 May 2017)
GOST 26487-85 http://docs.cntd.ru/document/gost-26487-85 (last access: 16 May 2017)
Hinton, T. G., Garnier-Laplace, J., Vandenhove, H., Dowdall, M., Adam-Guillermin, C., Alonzo, F., Barnett, C., Beaugelin-Seiller, K., Beresford, N. A., Bradshaw, C., Brown, J., Eyrolle, F., Fevrier, L., Gariel, J.-C., Gilbin, R., Hertel-Aas, T., Horemans, N., Howard, B. J., Ikäheimonen, T., Mora, J. C., Oughton, D., Real, A., Salbu, B., Simon-Cornu, M., Steiner, M., Sweeck, L., and Vives i Batlle, J.: An invitation to contribute to a strategic research agenda in radioecology, Environ. Radioactivity, 115, 73–82, doi:10.1016/j.jenvrad.2012.07.011, 2013.ISO 18589-5:2009 https://www.iso.org/standard/40877.html (last access 17 May 2017), 2013.
Ivanov, Yu A., Lewyckyj, N., Levchuk, S. E., Prister, B. S., Firsakova, S. K., Arkhipov, N. P., Arkhipov, A. N., Kruglov, S. V., Alexakhin, R. M., Sandalls, J., and Askbrant, S.: Migration of ^{137}Cs and ^{90}Sr from Chernobyl fallout in Ukrainian, Belarussian and Russian soils, Journal of Environmental Radioactivity, 35, 1, 1-21, 1997.
Izrael, Yu A., Vakulovskiy, S. M., Vetrov, V. A., Petrov, V. N., Rovynskiy, F. Ya. and Stukin, Ye. D.: Chernobyl: radioactive contamination of environment. Edited by Izrael YuA. Book Company “Gidrometeoizdat”, Leningrad, Russia. (In Russian), 1990.
Kal’chenko, V. M., Kholosha, V. I., Potikha V. M., Grebenyuk, A. V., Kovalsky, M. E., & Korzh, M. K.: Fulfilment of the National Programme on minimisation of consequences of Chernobyl accident in 1997. Chornobylinterinform, Kyiv, Ukraine. (In Ukrainian), 1998.
Kashparov, V. A., Ivanov, Yu A., Zvarich, S. I., Protsak, V. P., Khomutinin, Yu V., Kurepin, A. D. and Pazukhin, E. M.: Formation of Hot Particles During the Chernobyl Nuclear Power Plant Accident. Nuclear Technology, 114, 246-253, 1996.
Kashparov, V. A., Ivanov, Yu A., Protsak, V. P., Khomucinin, Yu V., Yoschenko, V. I., Pazukhin, E. M.: Assessment of the maximal temperature and of the duration of annealing of Chernobyl fuel particles during the accident. Radiokhimiya (Radiochemistry) 39, 1, 66-70 (in Russian), 1997.
Kashparov, V. A., Oughton, D. H., Zvarich, S. I., Protsak, V. P. and Levchuk, S. E.: Kinetics of fuel particle weathering and ^{90}Sr mobility in the Chernobyl 30-km exclusion zone. Health Physics, 76, 3, 251-259, 1999.
Kashparov, V. A., Lundin, S. M., Khomutinin, Yu V., Kaminsky, S. P., Levtchuk, S. E., Protsak, V. P., Kadygrib, A. M., Zvarich, S. I., Yoschenko, V. I. and Tschiersch, J.: Soil contamination with 90Sr in the near zone of the Chernobyl accident. Journal of Environment Radioactivity, 56, (3) 285-298, 2001.

Kashparov V. A.: Hot Particles at Chernobyl, Environmental Science and Pollution Research, 10, 1, 21-30, 2003.

Kashparov, V. A., Ahamdach, N., Zvarich, S. I., Yoschenko, V. I., Maloshtan, I. M. and Dewiere, L.: Kinetics of dissolution of Chernobyl fuel particles in soil in natural conditions. J. Environ. Radioact. 72, 335-353, doi:10.1016/j.jenvrad.2003.08.002, 2004.

Kashparov,V. A. Assessment of ecological risk caused by the long-living radionuclides in the environment. Ecotoxicology, Ecological Risk Assessment and Multiple Stressors, 155- 164. 2006

Kashparov, V. A., Levchuk, S., Protsak, V., Khomutinin, Yu, Maloshtan, I., Yoshenko, L., Otreshko, L., Pavlushenko, N., Kadygryb, A., Glukhovsky, A., Landshyn, V., Korol, V. and Lyubatchevskii, S. V.: Mapping the contamination of Ivankiv district territory with radionuclides Final report November 2013- September 2014 on the studies carried out by UIAR within the frameworks of contract No.2013-04 from 19/11/2013, 2014.

Kashparov V., Levchuk S., Zhurba M., Protsak V., Khomutinin Yu., Beresford N. A. and Chaplow J. S.: Spatial datasets of radionuclide contamination in the Ukrainian Chernobyl Exclusion Zone. NERC-Environmental Information Data Centre doi:10.5285/782ec845-2135-4698-8881-b38823e533bf, 2017.

Kazakov, S. V., Marchenko, V. I. and Sukhoruchkin, A. K.: Strontium-90 in the Exclusion zone and zone of unconditional evacuation. Bulletin of ecological situation in the Exclusion zone and zone of unconditional evacuation, 12, 38-41. (In Ukrainian), 1998.

Kerekes, A., Falk, R. and Suomela, J.: Analysis of hot particles collected in Sweden after the Chernobyl accident. Statens Stralskyddinstitut, SSI-rapport 91-02, 1991.

Khomutinin, Y. V., Kashparov, V. A. and Zhebrovska, K.I.: Sampling optimisation when radioecological monitoring, 160. Book publisher “VIPOL” Kiev, Ukraine, 2001.

Kuriny, V. D., Ivanov, Yu A., Kashparov, V. A., Loschilov, N. A., Protsak, V. P., Yudin, E. B., Zhurba, M. A. and Parshakov, A. E.: Particle associated Chernobyl fall-out in the local and intermediate zones. Annals of Nuclear Energy, 20, 6, 415-420, 1993.

Loshchilov, N. A., Kashparov, V. A., Yudin, Ye B., Protsak, V. P., Zhurba, M. A. and Parshakov, A. E.: Experimental assessment of radioactive fallout from the Chernobyl accident. Sicurezza e Protezione, 25-26, 46-49, 1991.

Mandjoukov, I. G., Burin, K., Mandjoukova, B., Vapirev, E. I. & Tsacheva T. S.: Spectrometry and visualization of ‘standard’ hot particles from the Chernobyl accident. Radiation Protection Dosimetry. 40, 235—244, 1992.Materon, G.: Basics of applied geostatistics. Book Company “Mir”, Moscow, Russia. (In Russian), 1968.

Møller A. P. and Mousseau T. A.: Efficiency of bio-indicators for low-level radiation under field conditions. Ecol Indicators 11:424–430, 2011.

Osuch, S., Dabrovska, M., Jaracz, P., Kaczanowski, J., Le Van Khoi., Mirowski, S., Piasecki, E., Szeflinska, G., Szeflinski, Z., Tropilo, J., Wilheimi, Z., Jastrzebski, J. and Pienkowski, L.: Isotopic composition of high-activity particles released in the Chernobyl accident. Health Physics. 57, 707-716, 1989.

Oughton, D. H., Salbu, B., Brand, T. L., Day, J. P. and Aarkrog, A.: Under-determination of strontium-90 in soils containing particles of irradiated uranium oxide fuel. Analyst, 118, 1101-1105, 1993.

Pavlotskaya, F.I.: Main principles of radiochemical analysis of environmental objects and methods of measurements of strontium and transuranium elements radionuclides. Journal of analytical chemistry, 52 (2), 126-143. (In Russian), 1997.

Salbu, B., Krekling, T., Oughton, D. H., Østby, G., Kashparov, V. A., Brand, T. L. and Day, J.P. Hot particles from accidental releases from Chernobyl and Windscale. Installations Analyst 119, 125-130, 1994.

Schubert, P. and Behrend, U.: Investigations of radioactive particles from the Chernobyl fall-out. Radiochimica Acta 41 (4), 149-155, 1987.

Shestopalov, V. M., Kashparov, V. A. and Ivanov Yu A.: Radionuclide Migration into the Geological Environment and Biota Accident. Environmental Science and Pollution Research, 10, 1, 39-47, 2003.

Smith, J. T. and Beresford, N. A.: Radioactive fallout and environmental transfers, in: Chernobyl – catastrophe and consequences, edited by: Smith, J. T. and Beresford, N. A., Chichester, Praxis Publishing/Springer, 35–80, 2005.

Sokolov, A. V. and Askinazi, D. L. (Eds): Agrochemical methods of soils study. Book Company “Nauka", Moscow, Russia. (In Russian), 1965.

SOU 74.14-37-424:2006. The quality of the soil. Determine the density of contamination of agricultural land anthropogenic radionuclides, Ukraine, 2006 (In Ukrainian).

Stolbovoi, V.: Soils of Russia: Correlated with the revised legend of the FAO soil map of the world and world reference base for soil resources. IIASA Research Report. IIASA, Laxenburg, Austria: RR-00-013 http://pure.iiasa.ac.at/6111, 2000, (last access 10 July 2017).

UIAR.: The map of the 30-km Chernobyl zone terrestrial density of contamination with strontium-90 (in 1997). UIAR, Kyiv, Ukraine, 1998.

UNSCEAR 1977 Report, Sources and effects of ionizing radiation, http://www.unscear.org/unscear/en/publications/1977.html, 1977 (last access 07 June 2017)

UNSCEAR 1988 Report, Sources, effects and risks of ionizing radiation, http://www.unscear.org/unscear/en/publications/1988.html, 1988 (last access 07 June 2017)

Steiner, M., Willrodt, C., Wichterey, K., Ikäheimonen, T., Ioshchenko, V., Hutri, K. L., Muikku, M., Outola, I., Beresford, N. A., Bradshaw, C., Dowdall, M., Eyrolle-Boyer, F., Guillevic, J., Hinton, T., Howard, B. J., Liland, A., Michalik, B., Mora, J. C., Oughton, D., Real, A., Robles, B., Salbu, B., Stark, K. and Sweeck, L.: Observatories for Radioecological Research –Description http://www.radioecology-exchange.org/sites/www.radioecology-exchange.org/files/STAR_Deliverable-2.3.pdf (last access 03 June 2017), 2013.

U.S.N.R.C.: https://www.nrc.gov/materials/fuel-cycle-fac/ur-enrichment.html (last access 12 June 2017), 2017.

Zhurba M., Kashparov V., Ahamdach N., Salbu B., Yoschenko V. and Levchuk S.: The "hot particles" data base. Radioactive Particles in the Environment, NATO Science for Peace and Security Series C: Environmental Security, ed. by D.Oughton, V. Kashparov, Published by Springer, the Netherlands 187-195 doi:10.1007/978-90-481-2949-2_12, 2009.