ASSESSMENT OF ^{90}Sr AND ^{137}Cs PENETRATION INTO REINFORCED CONCRETE (EXTENT OF 'DEEPENING') UNDER NATURAL ATMOSPHERIC CONDITIONS

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ABSTRACT

When assessing the feasibility of remediation following the detonation of a radiological dispersion device or improvised nuclear device in a large city, several issues should be considered including the levels and characteristics of the radioactive contamination, the availability of resources required for decontamination, and the planned future use of the city's structures and buildings. Currently, little is known about radionuclide penetration into construction materials in an urban environment. Knowledge in this area would be useful when considering costs of a thorough decontamination of buildings, artificial structures, and roads in an affected urban environment. Pripyat, a city substantially contaminated by the Chernobyl Nuclear Power Plant accident in April 1986, may provide some answers. The main objective of this study was to assess the depth of ^{90}Sr and ^{137}Cs penetration into reinforced concrete structures in a highly contaminated urban environment under natural weather conditions. Thirteen reinforced concrete core samples were obtained from external surfaces of a contaminated building in Pripyat. The concrete cores were drilled to obtain sample layers of 0-5, 5-10, 10-15, 15-20, 20-30, 30-40, and 40-50 mm. Both ^{90}Sr and ^{137}Cs were detected in the entire 0 – 50 mm profile of the reinforced cores sampled. In most of the cores, over 90% of the total ^{137}Cs inventory and 70% of the total ^{90}Sr inventory was found in the first 0-5 mm layer of the reinforced concrete. ^{90}Sr had penetrated markedly deeper into the reinforced concrete structures than ^{137}Cs.

Key words: Chernobyl, decontamination, reinforced concrete, Pripyat, ^{90}Sr, ^{137}Cs

INTRODUCTION

Various U.S. federal and international agencies have attempted to prepare for an event involving the detonation of a radiological dispersion device or improvised nuclear device. Some organizations have detailed the possible reasons, means, and consequences of such an event while others have attempted to develop the necessary models (Brown et al. 2006; IAEA 2002a; IAEA 2002b; IAEA 2009; PBS 2003; Thiessen et al. 1997, 2005a, 2005b, 2008, 2009). Among the significant issues to be addressed are the intensity and characteristics of the radioactive contamination, the availability of resources required for decontamination, and the planned future use of the city's buildings and infrastructure. However, several problems remain unsolved, including the consequent radionuclide penetration into construction materials in an urban environment. Knowledge in this area would help assess the costs of a thorough decontamination of buildings, artificial structures, and roads in an affected urban environment following a nuclear or radiological event.

At present, only one place exists where radioactive contamination in an urban environment can be studied: Pripyat, Ukraine. The borders of the highly contaminated city of Pripyat are located about 2.5–5 km away from the destroyed unit of the Chernobyl Nuclear Power Plant (ChNPP) (Fig. 1). Once a modern industrial city with a population of 55,000, Pripyat is now completely abandoned because it is part of the Chernobyl Exclusion Zone (ChEZ),[§] an area in the Ukraine heavily contaminated by radionuclides (e.g., ^{90}Sr, ^{137}Cs, and transuranics) from the ChNPP accident in April 1986. The Soviet Union government established the ChEZ soon after the accident. The ChEZ has its own administrative system, and its land is currently defined as *radiation hazardous land*, i.e., not to be used for human habitation or

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[§] Official Web site of the ChEZ Administration: http://www.ic-chernobyl.kiev.ua/

agricultural activities. Agricultural products generated there would not comply with the existing Ukrainian requirements on the maximum allowable radioactive concentration (Farfán et al. 2008).

Pripyat was contaminated by the radioactive fallout mainly in the form of finely dispersed nuclear fuel with a total deposition level of 80–24,000 kBq m^2 of ^{137}Cs, 50–6,660 kBq m^2 of ^{90}Sr, and 1.5–200 kBq m^2 of $^{239+240}Pu$ (Baryakhtar et al. 2003). An aerial gamma survey of Pripyat is illustrated in Fig. 2. Despite the decontamination efforts from 1986 to 1989, most buildings, structures, and roads are still highly contaminated in Pripyat, making it an ideal place to study radionuclide distribution, redistribution, and migration in an urban environment. So far there has been only one study involving radionuclide penetration into construction materials (Bondarkov et al. 2005), which was focussed on bricks. Concrete, the most common construction material, has remained unstudied.

METHODS AND RESULTS

The most contaminated area in Pripyat was selected, based on radiation survey data obtained by the Chernobyl Center's International Radioecology Laboratory (IRL)[**] (Fig. 2). ^{90}Sr and ^{137}Cs content was measured in 7 layers of 13 reinforced concrete core samples obtained from various parts of the easternmost building in Pripyat (Fig. 2). This building is a multi-wing four-story building of a former health center located on the shore of Yanovsky (or Pripyatsky) Backwater Pond (Figs. 2 and 3). It is oriented from west to east and appears to be the most contaminated building in Pripyat based on preliminary data obtained by IRL. The southern side of the building faces the ChNPP. The reinforced concrete core samples were obtained from the

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[**] Chernobyl Center for Nuclear Safety, Radioactive Waste and Radioecology: http://www.chornobyl.net/en/

lateral (vertical) surfaces of balconies on the first, second, and fourth floors of the southern and northern walls (Figs. 3 and 4).

The southern building wall is defined as a relatively dry wall since it is regularly lit by the sun. The northern wall is considered as a relatively wet wall. Immediately after the sampling, each reinforced concrete core sample was packed in such a way to prevent an uncontrolled redistribution of radioactive particles within one sample or among samples. Each sample was properly labeled. Two core samples were obtained from each floor chosen of the southern and northern facing walls, and one core sample was obtained from the building roof. The following three-symbol notation was used to indicate the locations in the building where the samples were obtained (Fig. 3): first symbol, D = Dry (southern facing wall), W = Wet (northern facing wall); second symbol, D = Down (first floor), M = Middle (second floor), U = Upper (fourth floor); and third symbol, 1 = first sample, 2 = second sample.

The beta flux was assessed in the 30 cm x 30 cm surface area surrounding the point where each reinforced concrete core sample was obtained (Fig. 5). A certified dosimeter-radiometer MKS-01R-01[††] with a BDKB-01R[‡‡] detector was used to obtain the beta particle flux measurements. The detector BDKB-01R uses anthracene, a fine crystalline organic scintillator, applied as a thin film on a truncated cone-shaped plexiglas light guide. From the outside, the scintillator is covered with several layers of light resistant aluminum film. The diameter of the measurement window is 6.5 cm. The detector design makes it possible to measure beta radiation if there is an associated background gamma radiation. For this purpose, the unit has a detachable aluminum alloy lid-filter installed on the side of the unit and does not change the measurements

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[††] MKS-01R-01 (or МКС-01Р-01 in Russian) is a universal dosimeter for measuring alpha, beta, gamma, and neutron radiation. It is commonly used in the Russian Federation and republics of the former Soviet Union. It can be obtained from Metra Telekom: http://www.priborkip.ru/pribor26737.html.

[‡‡] BDKB-01R (or БДКБ - 01Р in Russian) is a detection unit for beta flux measurements. It can be obtained from the Nuclear.Ru (Nuclear Site): http://www.nuclear.ru/rus/production/10/?from=180.

geometry regardless of whether the measurements are obtained with or without the shield. The BDKB-01R unit is also a highly sensitive device for measuring the equivalent gamma exposure dose, making it possible to take measurements for radiation levels comparable with the background. According to the applicable Ukrainian rules regarding use of this instrumentation, calibration is performed annually by the Ukrainian Center of Metrology Standardization with a calibration certificate being issued. IRL does not perform calibration because it does not have any authority to do so. The overall instrument beta efficiency, E_i, is 0.54 pulses per disintegration. The unit characteristics are presented in Table 1.

The detector was placed 1 cm above the surface. Two 100-second measurements in each location were taken, with and without a beta filter; only gamma irradiation is measured when the beta filter is used, and both beta and gamma irradiation are measured when the filter is not used. The beta particle flux was estimated as a difference between the two measurements. This was completed at five points in a 30 cm x 30 cm area surrounding each location where the reinforced concrete core samples were obtained.

The thirteen reinforced concrete cores were removed from the field and drilled under laboratory conditions. A 14-mm diameter drill was used to sample the following layers starting from 50 mm deep (the interior and less contaminated side of the wall) and going outward: 40-50, 30-40, 20-30, 15-20, 10-15, 5-10, and 0-5 mm. A total of 91 layer-by-layer samples were obtained. A gamma spectrometer Canberra Packard with a high purity Ge detector was used to measure ^{137}Cs content in each layer. A beta spectrometer with a thin filmed plastic scintillation detector was used to measure ^{90}Sr content. The measurement time was 12 hours. A complete description of this particular method was provided by Bondarkov et al. (2002).

A specially designed beta-spectrometer was used with a 60-mm diameter, thin-film plastic scintillation beta-detector mounted vertically to the counting chamber. It is shielded by 100–150 mm thick lead walls. An ASA100 analyzer is used for beta spectrum processing with ‘Beta+’ software (Institute of Nuclear Research, Ukraine). The unique feature of the system is the application of a method for non-radiochemical measurement of ^{90}Sr in thick-layer samples in the presence of comparable activities of ^{137}Cs. The method is based on the use of a thin-film plastic scintillation detector, the thickness (0.1 mm) of which allows the absorption of ^{90}Sr beta-electrons with an efficiency that is one or two orders of magnitude greater than that of the gamma-quanta of ^{137}Cs (^{137m}Ba – 661 keV). The detector is calibrated with standard ^{137}Cs and ^{90}Sr+^{90}Y sources (OISN-3 Applied Ecology Laboratory of ‘Environmental Safety Centre’, Odessa, Ukraine) and activity concentrations of approximately 110 kBq kg-1 (February 2007) for both ^{90}Sr and ^{137}Cs. After background subtraction, spectra obtained for the calibration phantoms were described by cubic splines, which were subsequently used to describe sample spectra.

The ^{90}Sr and ^{137}Cs concentrations in the 91 layers for the 13 concrete core samples are shown in Table 2 and Fig. 6. Both ^{90}Sr and ^{137}Cs were detected in the entire 0 – 50 mm profile of the reinforced cores sampled[§§]. In most of the cores, over 90% of the total ^{137}Cs inventory and 70% of the total ^{90}Sr inventory was found in the first 0-5 mm layer of the reinforced concrete. Under wet conditions (lower floors and the northern shaded side of the building), ^{90}Sr penetrated deeper into the reinforced concrete structures than ^{137}Cs. For ^{137}Cs, wet conditions seemed to have no effect. Concrete tends to crack over time forming tiny fissures and sometimes visible gaps. Water that penetrates reinforced concrete cavities through cracks functions as an “internal” radionuclide source.

[§§] It is possible that background levels ^{90}Sr and ^{137}Cs were present in the concrete prior to the Chernobyl Nuclear Power Plant accident due to global fallout. This is unlikely, however, since surface soil layers (which may have contained the fallout) were not used in making the concrete.

The surface contamination of construction materials as indicated by the beta flux had significant variability and high absolute values (10^1 - 10^3 particles cm^{-2} min^{-1}). There was practically no correlation between the radionuclide inventory in the 0-5 mm subsurface layer of the core and the average beta flux around the sampling point. The construction materials on the surfaces of the buildings facing the ChNPP were, in most cases, more contaminated than those facing away.

CONCLUSIONS

Both ^{90}Sr and ^{137}Cs were detected in the entire 50-mm profile of the reinforced cores sampled in Pripyat. In most of the cores, over 90% of the total ^{137}Cs inventory and 70% of the total ^{90}Sr inventory was found in the first 0-5 mm layer of the reinforced concrete. ^{90}Sr had penetrated noticeably deeper into the reinforced concrete structures than ^{137}Cs. Under wet conditions (lower floors and the northern shaded side of the building), ^{90}Sr penetrated deeper into the reinforced concrete structures than ^{137}Cs. For ^{137}Cs, wet conditions seemed to have no effect. There was no correlation between the radionuclide inventory in the 0-5 mm layer of the core and the average beta flux in the 30 cm x 30 cm surface area around the sampling point. (This may be an indication of extreme variability of fixed contamination over even a small surface area.) The construction materials on the surfaces of the buildings facing the ChNPP were, in most cases, more contaminated than those facing away. However, the beta flux measurements, though more variable facing away from the ChNPP, were not significantly different. This study may be a starting point for more elaborate studies involving various contaminated tall buildings and structures in Pripyat at various distances from the ChNPP.

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<u>Figures</u>:

Fig. 1 - The City of Pripyat, Ukraine. The borders of Pripyat are 2.5–5 km away from the destroyed ChNPP Reactor Unit Number 4.

Fig. 2 - Initial radioactive fallout in the City of Pripyat, Ukraine after the 1986 ChNPP accident (1992 aerial gamma survey). Provided by the Chernobyl Center, Slavutich, Ukraine.

Fig. 3 - Four-story multi-wing building where the reinforced concrete core samples were obtained from in Pripyat, Ukraine. The three-letter symbols mean the following: first symbol, D = Dry (southern facing wall), W = Wet (northern facing wall); second symbol, D = Down (first floor), M = Middle (second floor), U = Upper (fourth floor); and third symbol, 1 = first sample, 2 = second sample.

Fig. 4 - Obtaining the reinforced concrete core samples. A) drilling the reinforced concrete. B) Hole for DD1 sample. C) Concrete core sample. D) Drilling the concrete core. E) Obtaining layer-by-layer samples. F) Five of seven layer samples.

Fig. 5 - Mean beta flux measurements and their standard error. These measurements were taken in the locations where the reinforced concrete core samples were obtained.

Fig. 6 - ^{137}Cs and ^{90}Sr content in the layer-by-layer samples of the reinforced concrete core samples. The three-symbol notation is the same as that of Fig. 3.

Table 2 Footnotes:

[a] "Data" denotes the measurement result.
[b] "Uncertainty" denotes a measurement uncertainty associated with the measurement
result.
[c] "MDA" means the measurement results are below the minimum detectable activity; therefore, the value of minimally detectable activity is provided.

Footnotes (Text):

[*] Savannah River National Laboratory, Aiken, SC 29808, USA

[†] Chernobyl Center for Nuclear Safety, Radioactive Waste and Radioecology, International Radioecology Laboratory, 07100, Slavutych, Ukraine

[‡] Centers for Disease Control and Prevention, Atlanta, GA 30333, USA

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[††] MKS-01R-01 (or MKC-01P-01 in Russian) is a universal dosimeter for measuring alpha, beta, gamma, and neutron radiation. It is commonly used in the Russian Federation and republics of the former Soviet Union. It can be obtained from Metra Telekom: http://www.priborkip.ru/pribor26737.html.

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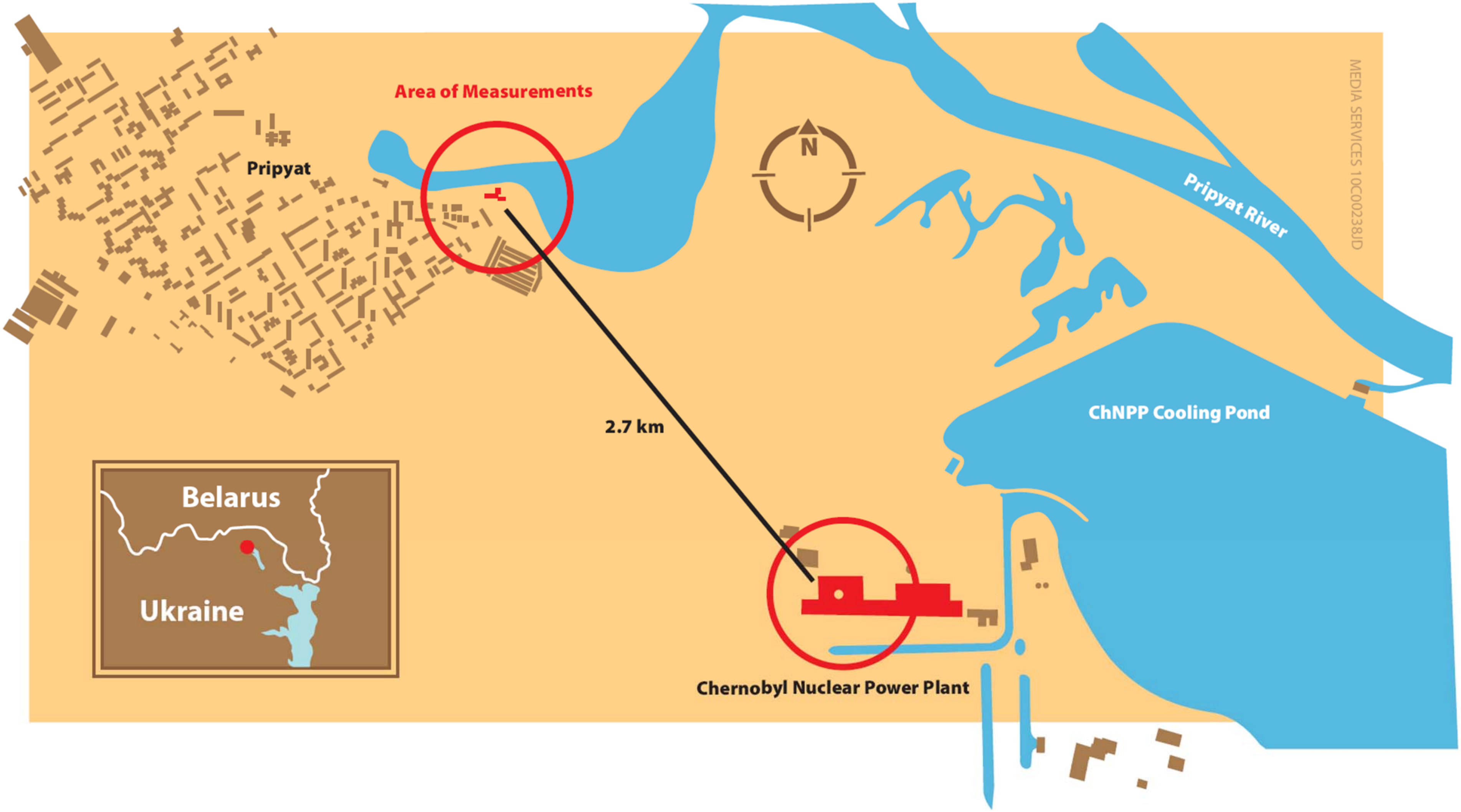


Fig. 1. The City of Pripyat, Ukraine. The borders of Pripyat are 2.5–5 km away from the destroyed ChNPP Reactor Unit Number 4.

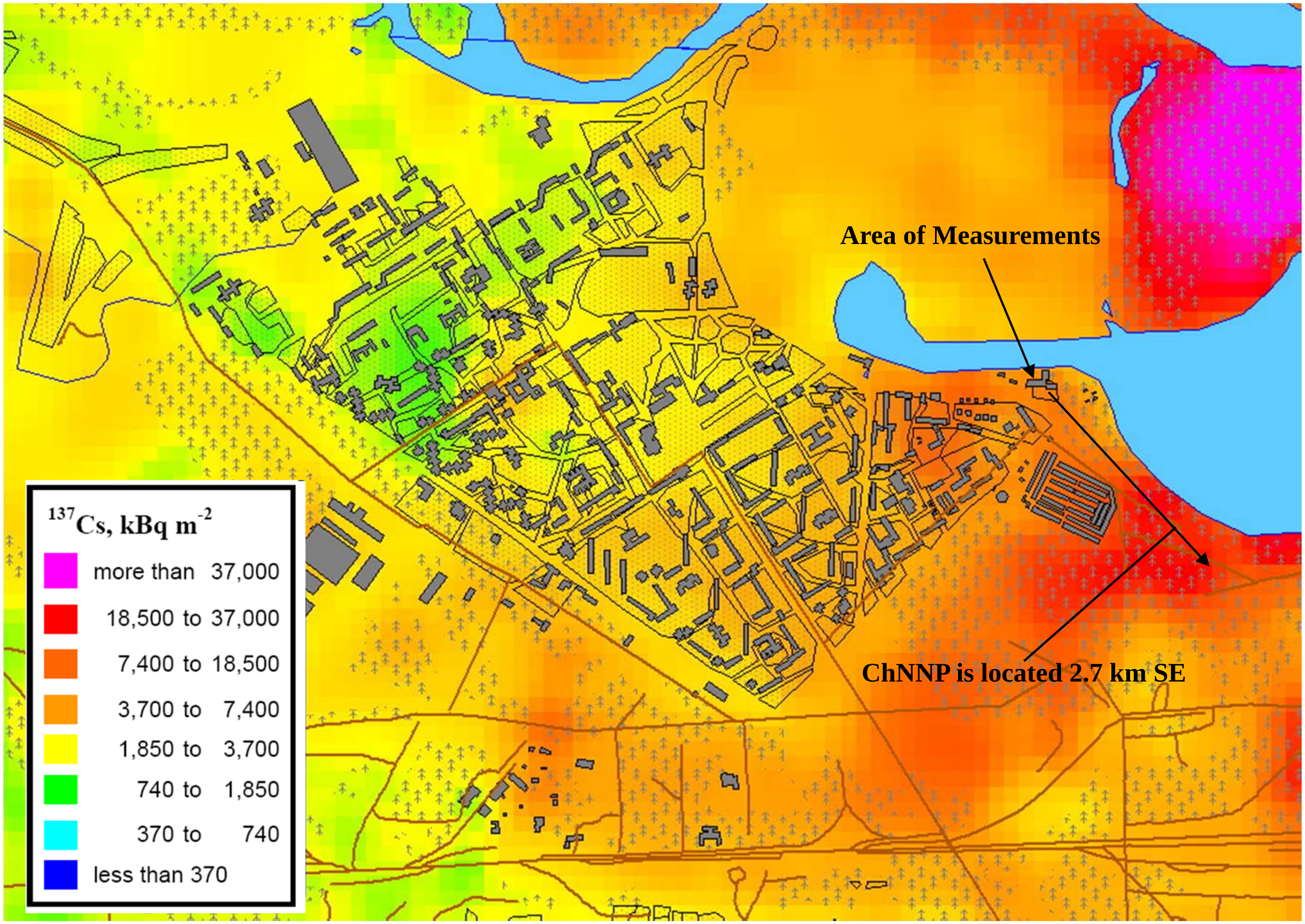


Fig. 2. Initial radioactive fallout in the City of Pripyat, Ukraine after the 1986 ChNPP accident (1992 aerial gamma survey). Provided by the Chernobyl Center, Slavutich, Ukraine.

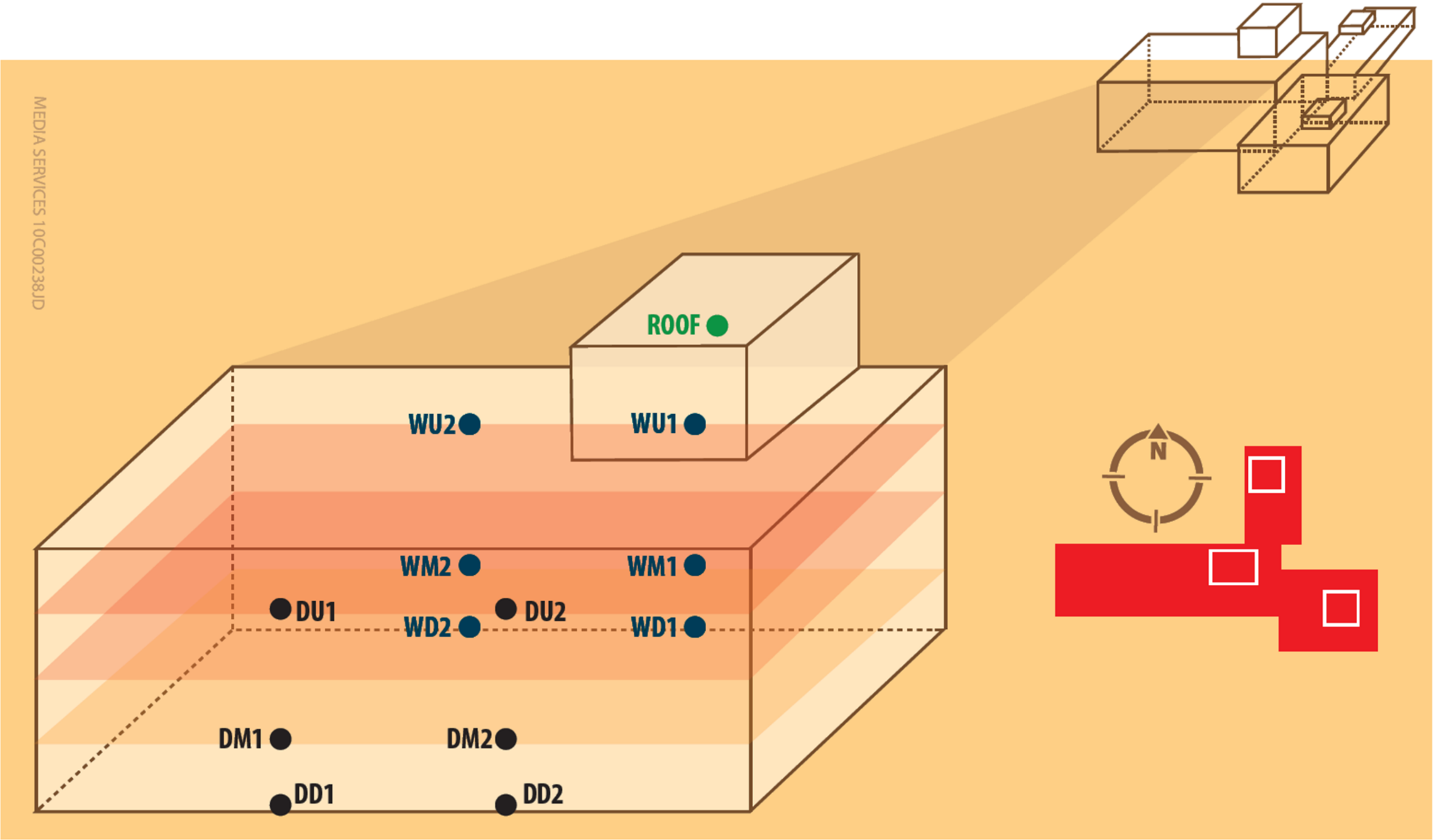
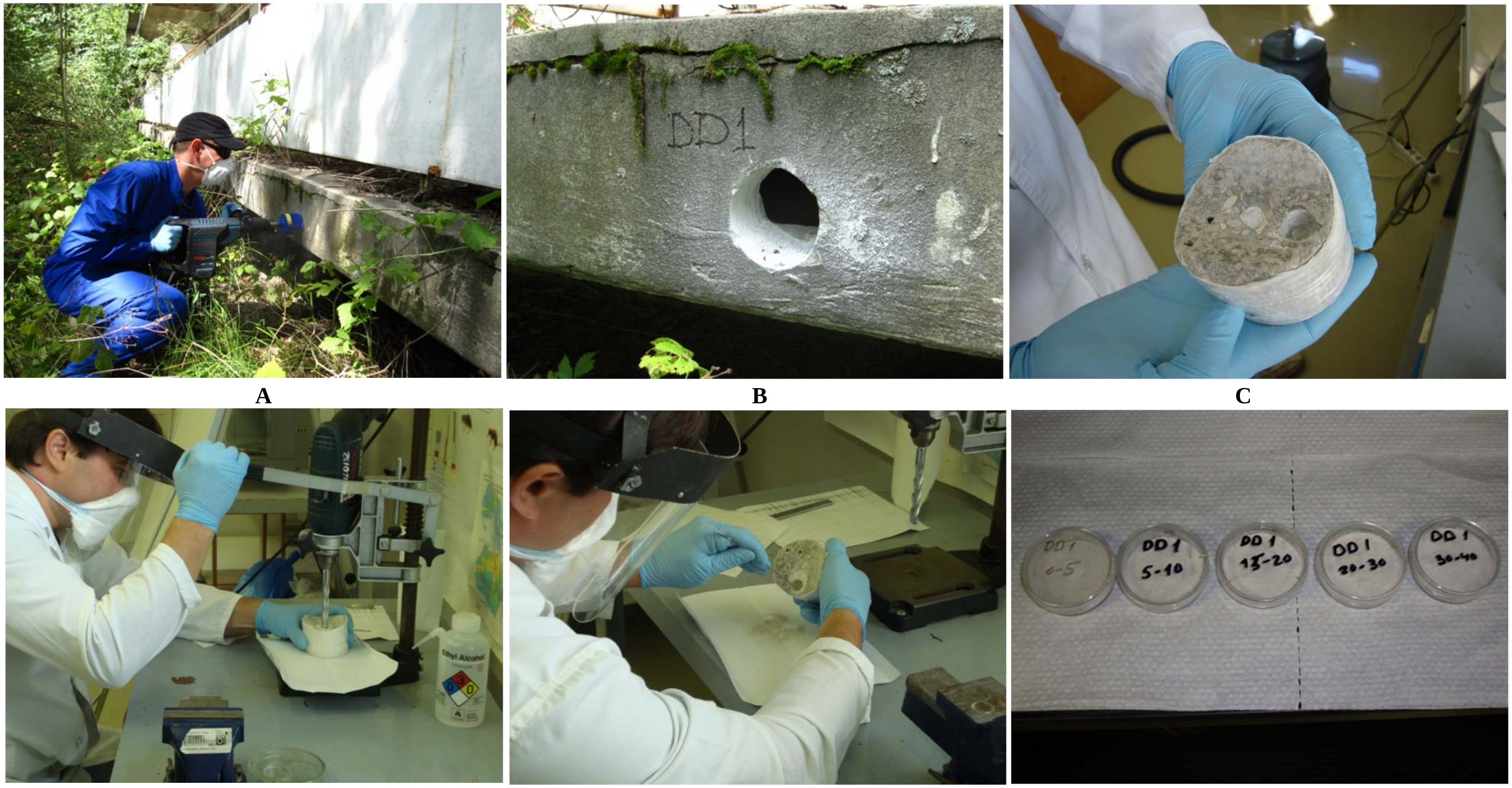


Fig. 3. Four-story multi-wing building where the reinforced concrete core samples were obtained from in Pripyat, Ukraine. The three-letter symbols mean the following: first symbol, D = Dry (southern facing wall), W = Wet (northern facing wall); second symbol, D = Down (first floor), M = Middle (second floor), U = Upper (fourth floor); and third symbol, 1 = first sample, 2 = second sample.



A **B** **C**

D **E** **F**

Fig. 4. Obtaining the reinforced concrete core samples. A) drilling the reinforced concrete. B) Hole for DD1 sample. C) Concrete core sample. D) Drilling the concrete core. E) Obtaining layer-by-layer samples. F) Five of seven layer samples.

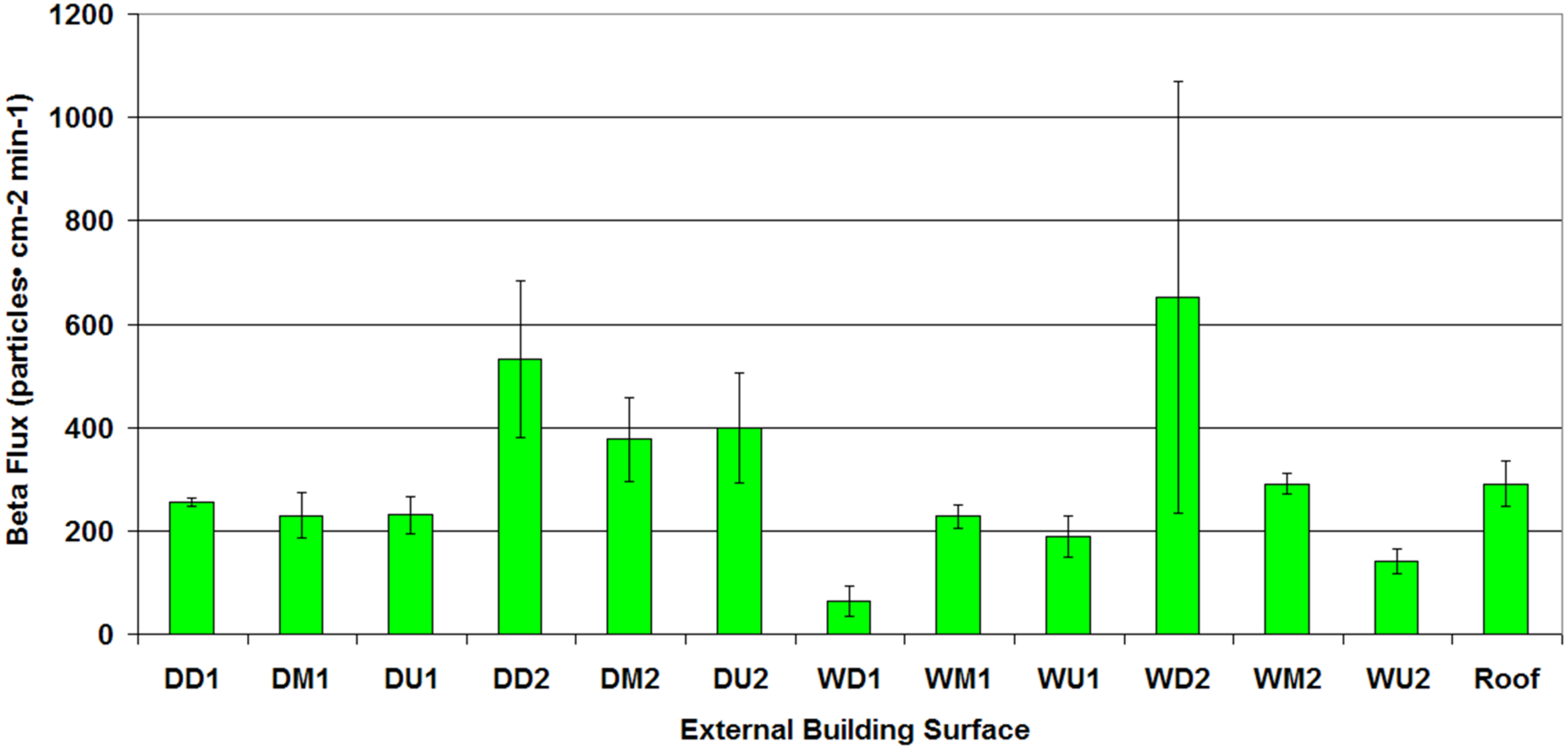


Fig. 5. Mean beta flux measurements and their standard error. These measurements were taken in the locations where the reinforced concrete core samples were obtained.

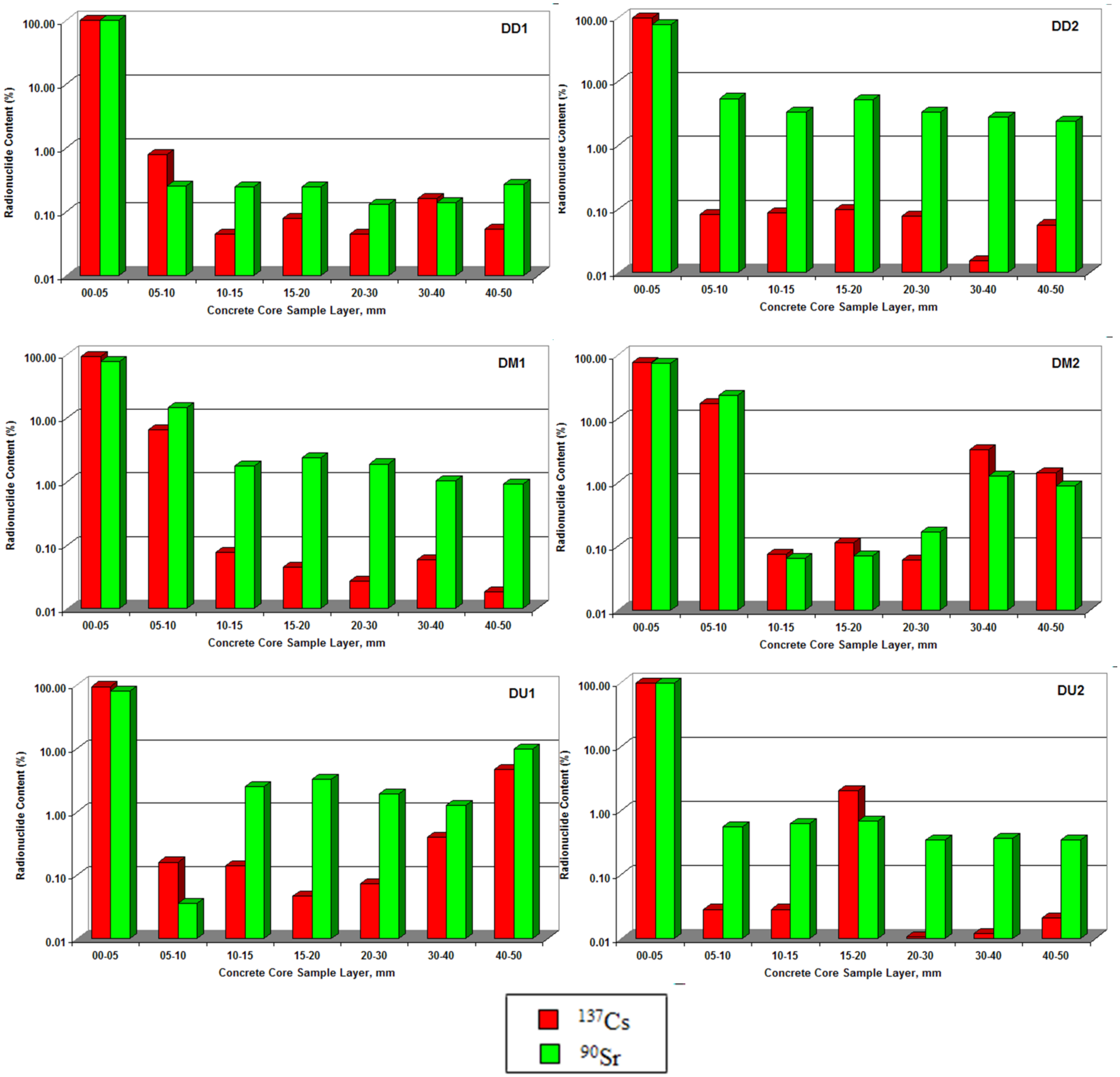


Fig. 6. ^{137}Cs and ^{90}Sr content in the layer-by-layer samples of the reinforced concrete core samples. The three-symbol notation is the same as that of Fig. 3.

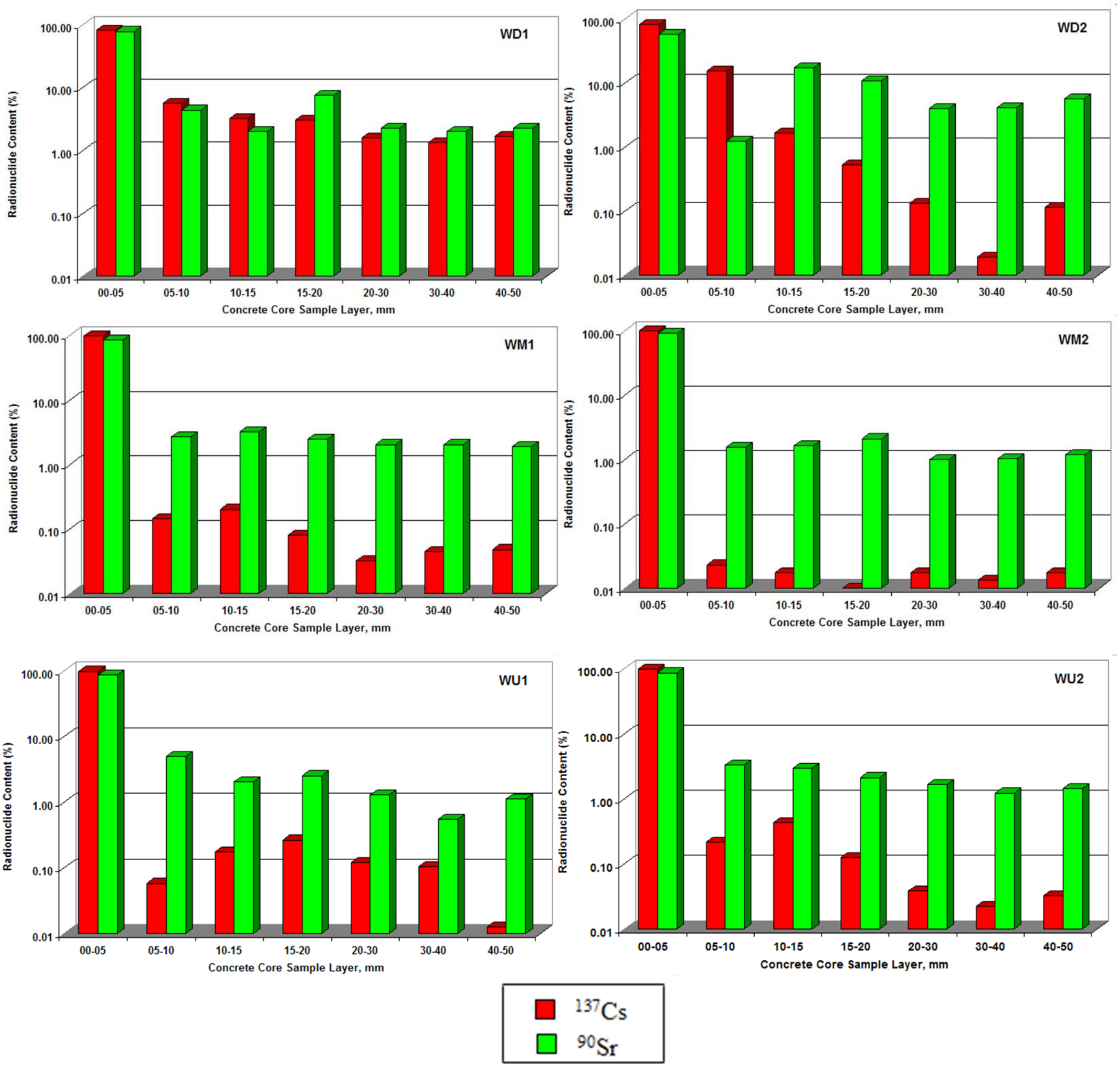


Fig. 6 Cont. ^{137}Cs and ^{90}Sr content in the layer-by-layer samples of the reinforced concrete core samples. The three-symbol notation is the same as that of Fig. 3.

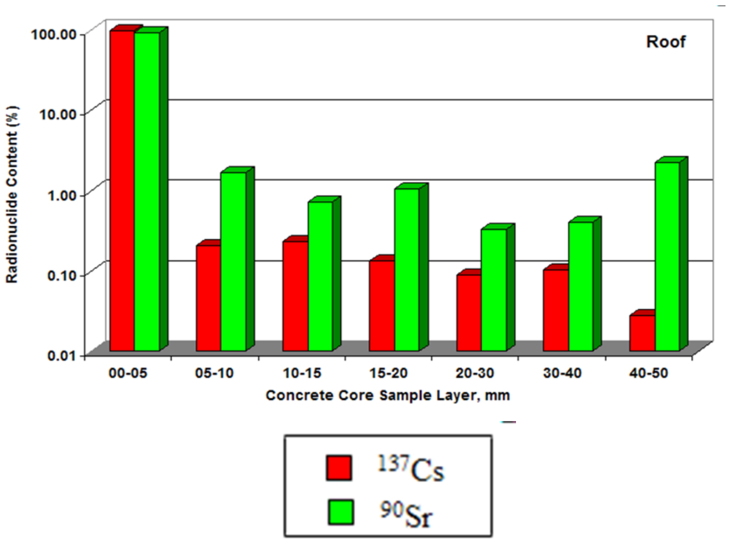


Fig. 6 Cont. ^{137}Cs and ^{90}Sr content in the layer-by-layer samples of the reinforced concrete core samples. The three-symbol notation is the same as that of Fig. 3.

Table 1. Detector BDKB-01R characteristics.

Type of radiation	**Measured value**	**Measurements range**	**Power range for the measured radiation**	**Total error, %**
Beta	Beta flux, particles cm^{-2} min	1 – 10^{5}	0.3 – 3 MeV of the maximum value of the beta spectrum energies	±20
Gamma	Equivalent dose rate, µSv h^{-1}	0.1 – 10^{4}	0.125 – 1.25 MeV	±20

Table 2. ^{137}Cs and ^{90}Sr content in layer-by-layer reinforced concrete samples.

Sample Point	Sample Number	Layer, mm	Layer Mass, g	^{137}Cs, Bq g^{-1}		^{90}Sr, Bq g^{-1}	
				Data[a]	Uncertainty[b, c]	Data[a]	Uncertainty[b, c]
DD1	G007845	00-05	1.657	11.163	1.303	12.657	0.057
	G007846	05-10	1.886	0.090	0.018	0.032	<MDA
	G007847	10-15	1.957	0.005	0.009	0.031	<MDA
	G007848	15-20	1.956	0.009	0.012	0.031	<MDA
	G007849	20-30	3.540	0.005	0.005	0.017	<MDA
	G007850	30-40	3.418	0.018	<MDA	0.018	<MDA
	G007851	40-50	1.762	0.006	0.010	0.034	<MDA
DD2	G007852	00-05	2.002	19.473	2.236	5.711	0.105
	G007853	05-10	1.470	0.016	0.003	0.396	0.034
	G007854	10-15	1.963	0.017	0.004	0.244	0.020
	G007855	15-20	1.344	0.019	0.005	0.376	0.037
	G007856	20-30	3.596	0.015	0.002	0.240	0.031
	G007857	30-40	3.596	0.003	0.004	0.205	0.033
	G007858	40-50	3.277	0.011	0.002	0.177	0.015
DM1	G007859	00-05	1.917	20.449	2.431	15.039	0.099
	G007860	05-10	2.299	1.448	0.172	2.797	0.037
	G007861	10-15	1.753	0.017	0.004	0.342	0.029
	G007862	15-20	1.965	0.010	0.003	0.457	0.056
	G007863	20-30	3.527	0.006	0.002	0.368	0.020
	G007864	30-40	3.433	0.013	0.003	0.198	0.015
	G007865	40-50	3.911	0.004	0.002	0.176	0.010
DM2	G007866	00-05	2.148	21.555	1.611	32.447	0.134
	G007867	05-10	1.741	4.865	0.402	10.075	0.043
	G007868	10-15	2.121	0.021	0.009	0.028	<MDA
	G007869	15-20	1.917	0.032	<MDA	0.031	<MDA
	G007870	20-30	3.549	0.017	0.008	0.073	0.015
	G007871	30-40	3.709	0.908	0.090	0.553	0.154
	G007872	40-50	3.434	0.393	0.034	0.387	0.015
DU1	G007873	00-05	2.797	14.033	1.595	8.920	0.054
	G007874	05-10	1.514	0.024	0.004	0.004	0.034
	G007875	10-15	2.022	0.021	0.004	0.272	0.019
	G007876	15-20	1.604	0.007	0.000	0.364	0.024
	G007877	20-30	4.174	0.011	0.002	0.212	0.029
	G007878	30-40	4.447	0.060	0.007	0.141	0.009
	G007879	40-50	2.743	0.700	0.081	1.079	0.050
DU2	G007880	00-05	2.633	65.325	4.949	46.415	0.380
	G007881	05-10	1.956	0.019	0.005	0.265	0.026
	G007882	10-15	1.912	0.019	0.004	0.299	0.026
	G007883	15-20	1.728	1.369	0.005	0.323	0.023
	G007884	20-30	3.719	0.007	1.767	0.166	0.011
	G007885	30-40	3.235	0.008	0.002	0.174	0.012
	G007886	40-50	3.271	0.014	<MDA	0.166	0.015
WD1	G007887	00-05	1.993	1.633	0.122	2.135	0.032
	G007888	05-10	1.092	0.110	<MDA	0.119	0.054
	G007889	10-15	1.833	0.063	0.022	0.055	0.038
	G007890	15-20	1.674	0.060	<MDA	0.203	0.036
	G007891	20-30	3.276	0.031	<MDA	0.061	<MDA
	G007892	30-40	3.616	0.026	<MDA	0.055	<MDA
	G007893	40-50	3.227	0.033	<MDA	0.062	<MDA

Table 2 Cont. ^{137}Cs and ^{90}Sr content in layer-by-layer reinforced concrete samples.

Sample Point	**Sample Number**	**Layer, mm**	**Layer Mass, g**	**^{137}Cs, Bq g^{-1}**		**^{90}Sr, Bq g^{-1}**	
				Data[a]	**Uncertainty**[b, c]	**Data**[a]	**Uncertainty**[b, c]
WD2	G007894	00-05	1.258	17.337	0.126	3.390	0.078
	G007895	05-10	1.057	3.211	0.242	0.072	4.607
	G007896	10-15	1.947	0.344	0.033	1.008	0.026
	G007897	15-20	1.187	0.110	<MDA	0.632	0.051
	G007898	20-30	3.470	0.028	<MDA	0.236	0.550
	G007899	30-40	3.151	0.004	<MDA	0.240	0.552
	G007900	40-50	4.015	0.024	<MDA	0.331	0.015
WM1	G007901	00-05	1.603	30.848	3.431	7.211	0.143
	G007902	05-10	2.259	0.045	0.007	0.230	0.018
	G007903	10-15	2.026	0.063	0.009	0.274	0.025
	G007904	15-20	2.637	0.025	0.005	0.211	0.015
	G007905	20-30	3.496	0.010	0.002	0.173	0.011
	G007906	30-40	3.146	0.014	0.003	0.173	0.016
	G007907	40-50	3.337	0.015	0.004	0.162	0.015
WM2	G007908	00-05	1.746	52.52	5.842	16.239	0.384
	G007909	05-10	2.362	0.012	0.003	0.277	0.021
	G007910	10-15	2.406	0.009	0.002	0.292	0.021
	G007911	15-20	2.392	0.001	0.005	0.373	0.033
	G007912	20-30	3.614	0.009	0.003	0.176	0.014
	G007913	30-40	3.588	0.007	0.002	0.184	0.014
	G007914	40-50	3.279	0.009	0.002	0.212	0.015
WU1	G007915	00-05	2.344	24.066	1.752	7.913	0.038
	G007916	05-10	2.117	0.014	0.014	0.451	0.028
	G007917	10-15	2.385	0.042	<MDA	0.185	0.025
	G007918	15-20	1.886	0.064	<MDA	0.229	0.032
	G007919	20-30	3.380	0.029	<MDA	0.117	0.015
	G007920	30-40	3.972	0.025	<MDA	0.050	<MDA
	G007921	40-50	3.938	0.003	<MDA	0.102	0.013
WU2	G007922	00-05	2.337	30.535	3.398	11.714	0.094
	G007923	05-10	2.100	0.067	0.012	0.444	0.052
	G007924	10-15	1.727	0.134	0.016	0.405	0.023
	G007925	15-20	2.006	0.039	<MDA	0.287	0.020
	G007926	20-30	3.695	0.012	0.002	0.224	0.011
	G007927	30-40	3.778	0.007	0.003	0.167	0.013
	G007928	40-50	3.634	0.010	0.002	0.193	0.011
Roof	G007929	00-05	2.578	28.538	2.074	13.929	0.050
	G007930	05-10	1.791	0.060	0.017	0.250	0.034
	G007931	10-15	1.833	0.068	<MDA	0.109	<MDA
	G007932	15-20	2.447	0.039	<MDA	0.158	0.025
	G007933	20-30	4.065	0.026	<MDA	0.049	<MDA
	G007934	30-40	3.303	0.030	<MDA	0.061	<MDA
	G007935	40-50	3.266	0.008	0.009	0.333	0.018

[a] "Data" denotes the measurement result.

[b] "Uncertainty" denotes a measurement uncertainty associated with the measurement result.

[c] "MDA" means the measurement results are below the minimum detectable activity; therefore, the value of minimum detectable activity is provided.