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*Manuscript (Abstract, Text, References, Footnotes, List of Figure Captions)

ASSESSMENT OF BETA PARTICLE FLUX FROM SURFACE CONTAMINATION AS A RELATIVE INDICATOR FOR RADIONUCLIDE DISTRIBUTION ON EXTERNAL SURFACES OF A MULTISTORY BUILDING IN PRIPYAT

Eduardo B. Farfán,* Sergii P. Gaschak,† Andriy M. Maksymenko,† G. Tim Jannik,* James C. Marra,* Mikhail D. Bondarkov,† and Elizabeth H. Donnelly‡

*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

For reprints and correspondence contact:

Eduardo B. Farfán, Ph.D.
Environmental Dosimetry Group
Environmental Science and Biotechnology
Savannah River National Laboratory
Savannah River Nuclear Solutions, LLC
Bldg. 773-42A, Room 236
Aiken, SC 29808
E-mail: Eduardo.Farfan@srnl.doe.gov
Phone: (803) 725-2257
Fax: (803) 725-7673

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Abstract

Several issues should be considered when assessing the feasibility of remediation following the detonation of a radiological dispersion device (e.g., dirty bomb) or improvised nuclear device in a large city. These issues include 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. Presently, little is known about the distribution, redistribution, and migration of radionuclides in an urban environment. However, 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 determine the radionuclide distribution on a Pripyat multistory building that had not been decontaminated and, therefore, could reflect the initial fallout and its further natural redistribution on external surfaces over 23 years. The 7-story building selected was surveyed from the ground floor to the roof on horizontal and vertical surfaces along seven ground-to-roof transections. Some results from this study indicate that the upper floors of the building had higher contamination levels than the lower floors. Consequently, the authors recommend that thorough decontamination should be considered for all the floors of tall buildings (not just lower floors).

Key words: Chernobyl, decontamination, beta particle flux, Pripyat

INTRODUCTION

The fear that terrorists might use radiological dispersal devices, nuclear explosive devices, or nuclear materials as part of an improvised nuclear device (IND) in an attack has increased over the last few years. An early attempt at such an attack involved Chechen rebels who placed a ^{137}Cs source covered with explosives in the Izmaylovsky Park in Moscow in 1995 (IAEA 2002a). The device was never activated, but the incident caused anxiety among the public as well as local and international agencies.

A major concern of law enforcement agencies is the relatively easy access terrorist groups throughout the world have to radiation sources. In Kabul, in April 2002, International Atomic Energy Agency (IAEA) experts secured several unguarded Soviet-made radiation sources, including a powerful ^{60}Co source once used in medical and research applications (IAEA 2002b). Evidence has shown that 'small dirty bombs' have been constructed from radioactive sources of medical devices (PBS 2003).

As a first major step to locate, recover, secure, and dispose (or recycle) orphan radioactive sources[§] throughout the republics of the former Soviet Union, the U.S. Department of Energy, IAEA, and Russian Federation's Ministry for Atomic have established a working group on securing and managing radioactive sources (IAEA 2002a). Highly enriched uranium and plutonium could be used to build an IND with relatively little processing. The key concern is that organized trafficking in materials of nuclear weapons might occur undetected (IAEA 2009).

[§]*Orphaned radioactive sources* is a term used to denote radioactive sources that are not under official regulatory control. Orphan sources are a common occurrence in the republics of the former Soviet Union, but the U.S. Nuclear Regulatory Commission reports that U.S. companies have also lost track of more than 1,500 radioactive sources since 1996 and more than half were never recovered. A European Union (EU) study estimated that up to 70 sources are lost from regulatory control in the EU every year. A European Commission report estimated that more than 30,000 abandoned sources in the EU are held at the users' premises almost unprotected, thus putting these sources at risk of being lost from regulatory control (IAEA 2002a).

Various U.S. federal agencies have attempted to prepare for such an event. However, several problems remain unsolved, including radionuclide vertical distribution on tall buildings and structures and the consequent fixation, distribution, and redistribution of contamination 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. 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, very little is known about the dispersion and redispersion of radionuclides in an urban environment.

Currently, only one place exists where radioactive contamination in an urban environment could 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 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

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

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.

The data from this study and similar studies should help verify and validate current and future models developed and being developed by various international organizations. For instance, IAEA's Working Group 9 Environmental Modeling for Radiation Safety (EMRAS II)[††] was established to improve modeling and assessment capabilities for remediating urban areas contaminated with dispersed radionuclides, including the consequences of countermeasures. Various studies (e.g., Brown et al. 2006; Hoffman and Thiessen 1995; Thiessen et al. 1997, 2005a, 2005b, 2008, 2009) have addressed modeling of urban contamination; however, modeling of radiation exposures in contaminated urban environments is still fairly undeveloped compared with other types of assessment models. These studies clearly show that much more data on urban contamination and countermeasures are still needed for model verification and validation.

METHODS AND RESULTS

The most contaminated area in Pripyat was selected for this study on the basis of radiation survey data obtained by the Chernobyl Center's International Radioecology Laboratory (IRL)[‡‡] (Fig. 2). The objective of this study was to determine the radionuclide distribution on a multistory building in Pripyat from the floor level to the roof by obtaining surface contamination

[††]IAEA's EMRAS II Web site: http://www-ns.iaea.org/projects/emras/emras2/default.htm
[‡‡]Chernobyl Center for Nuclear Safety, Radioactive Waste and Radioecology: http://www.chornobyl.net/en/

beta particle flux measurements and considering two building sides (one facing the ChNPP Reactor Unit Four and the other facing away).

A certified dosimeter-radiometer MKS-01R-01[§§] with a BDKB-01R[***] detector was used for obtaining 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 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 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.

[§§]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.

The easternmost multistory building in the city of Pripyat was selected to assess beta flux from vertical and horizontal surfaces (Figs. 1 and 2). That building is an unfinished 7-story hospital located in the trajectory of the northern radioactive plume. The structure consists of reinforced concrete covered with small ceramic tiles on all areas other than the seams and lateral surfaces. The building extends from southeast to northwest so that its northeast and southeast walls face the ChNPP, while its southwest and northwest sides do not face the plant (Fig. 3).

The building length, width, and height are 67.0, 22.5, 27.0 m, respectively. The building is a seven-story building with an equipment floor (eighth floor). All floors, with the exception of the equipment floor, have 1.7 x 1.7 m windows along the entire perimeter (Fig. 4). At the time of the accident, the building was undergoing interior renovations with utilities lines being installed there. By the time the measurements were obtained in the building, some of the glass windows had been broken due to wind or human activities. Because it was unfinished, the building was assumed not to be decontaminated. Therefore, the contamination distribution on the building's external surface should reflect the initial fallout and its further natural redistribution over 23 years. This assumption was verified when the contamination levels on the ground floor were found to be similar to the levels found on the roof. Also, the contamination levels on the external walls facing away from the ChNPP were found to be lower than on the walls that faced the ChNPP.

Seven vertical ground-to-roof transections were selected on the external surface of the building that included a window on each floor (Fig. 3): three transections (A–C) were on its northeastern side, three (D–F) on its southwestern side, and one (G) on its southeastern side. Each transection contained seven measurement points at various levels: ground level, the first floor, the second floor, the fourth floor, the sixth floor, the seventh floor, and the roof. In most of these locations, measurements were conducted in the lower part of the window frames.

For each measurement point on floors 1, 2, 4, 6, and 7, two beta flux measurements were taken inside the window recess; the first measurement was obtained on the vertical surface inside the recess 30 cm above the window sill, and the second measurement was obtained on the window sill 30 cm away from the side where the first measurement had been taken (Fig. 4). In all measurements, the vertical surface used was the one that faced the ChNPP. On the roof, measurements were obtained on vertical and adjacent horizontal surfaces of the lateral-reinforced concrete fencing. At the ground level many of the sills were covered with metal ledges at the time of the accident which had later been removed. Therefore, the ground floor measurements were obtained as follows: The first measurement point was taken on the vertical surface of the lower part of the building (30 cm above the ground level) and the second measurement was taken on the ground level 30 cm away from the building (Fig. 4).

In total, 48 measurements on horizontal surfaces and 48 measurements on adjacent vertical surfaces were obtained in August 2009 (more than 23 years after the accident). The ratios of beta particle flux on the ground level to the mean beat flux for horizontal and vertical surfaces along the seven transections are graphically presented in Fig. 5. The ratios for the vertical transections facing the ChNPP are shown in Fig. 5 A–C and G.

The external surface contamination of the building considered in this study has a significant variability and high absolute values (10^2–10^3 particles cm^2 min^{-1}) as indicated by the beta particle flux measurements. In most cases, the horizontal surfaces are more contaminated than the adjacent vertical surfaces by a few factors of magnitude. In general, the ground near the building (horizontal measurements) is the most contaminated. The external surfaces of the building facing the ChNPP are generally more contaminated. Most of the time, the contamination of the building's external surfaces facing the ChNPP decreased going from lower floors to higher floors. However, when the building surfaces not facing the ChNPP are considered, the upper floors have a higher contamination than lower floors.

CONCLUSIONS

National and international organizations have addressed the possible use of nuclear or radiological materials by extremists. Several studies have attempted to help address the remediation issue by modeling radiation exposures in contaminated urban environments; however, this type of modeling is still quite undeveloped compared with other types of assessment models. In addition, data on urban contamination, decontamination, and countermeasures are still needed for model verification and validation. This study focused only on one aspect of this major issue: vertical contamination on tall buildings. Some of the study's results indicate that the upper floors are more contaminated than lower floors for the building side not facing the ChNPP; therefore, thorough decontamination should be considered for all the floors of tall buildings (not just lower floors). Even though its results are preliminary, 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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Figure Captions:

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 - Building where measurements were made, Pripyat, Ukraine. a) Southeast side of the building (Transection G facing ChNNP). b) Aerial view depicting the seven transections. Transections A, B, C and G face ChNNP.

Fig. 4 - Measurement points for floors 1, 2, 4, 6, and 7 inside each window recess (A: vertical surface, B: horizontal surface) at the study location in Pripyat, Ukraine.

Fig. 5 - Ratio of beta particle flux on the ground level to the mean beat flux for horizontal and vertical surfaces along the seven transections at the study location in Pripyat, Ukraine. Transections A, B, C, and G face the ChNNP.

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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

[§] *Orphaned radioactive sources* is a term used to denote radioactive sources that are not under official regulatory control. Orphan sources are a common occurrence in the republics of the former Soviet Union. Even the U.S. Nuclear Regulatory Commission reports that U.S. companies have lost track of more than 1,500 radioactive sources since 1996 and more than half were never recovered. A European Union (EU) study estimated that up to 70 sources are lost from regulatory control in the EU every year. A European Commission report estimated that more than 30,000 abandoned sources in the EU are held at the users' premises almost unprotected, thus putting these sources at risk of being lost from regulatory control (IAEA 2002a).

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

[††] IAEA's EMRAS II Web site: http://www-ns.iaea.org/projects/emras/emras2/default.htm

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

[§§] 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.

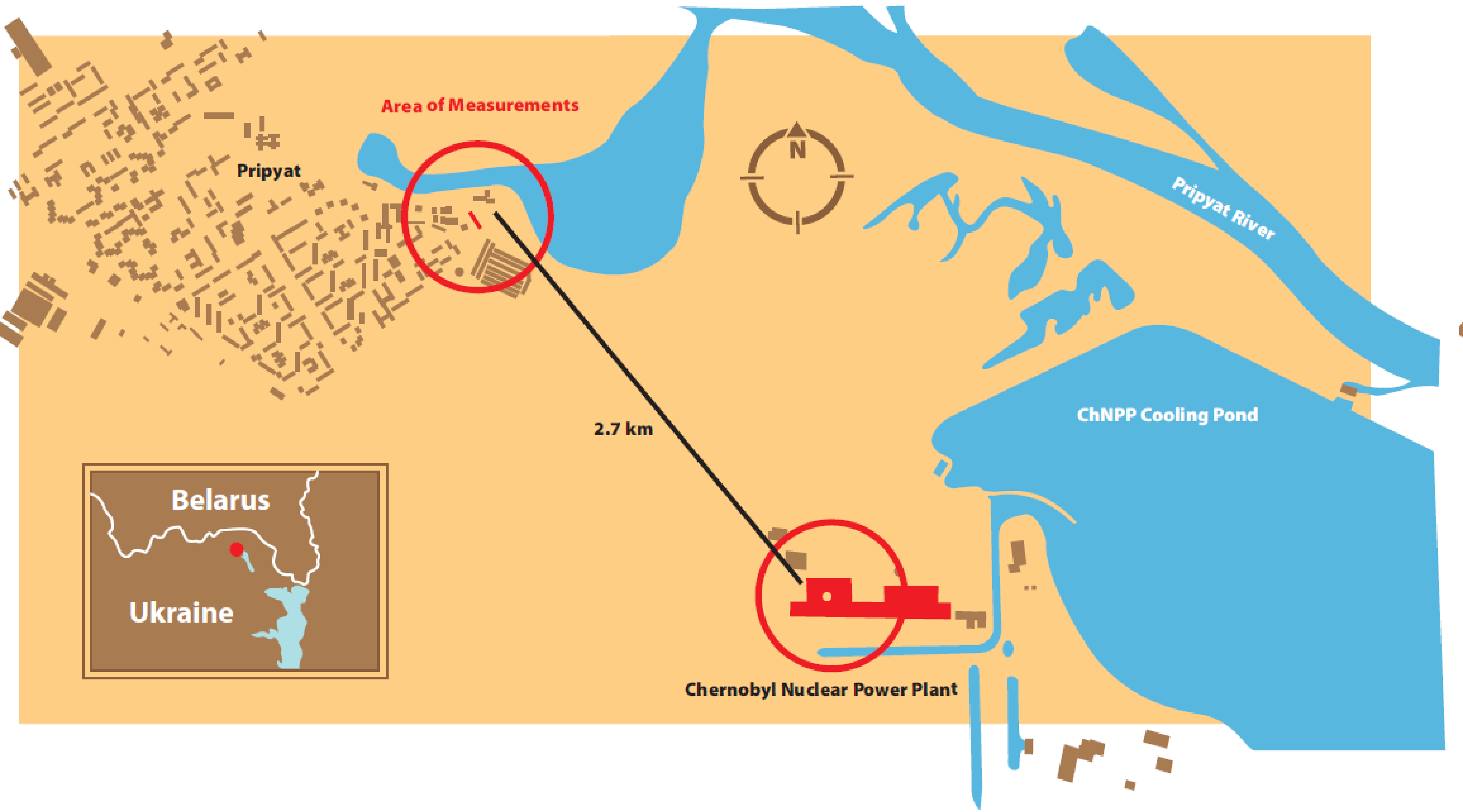
*** BDKB-01R (or БДКБ – 01Р in Russian) is a detection unit for beta flux measurements. It can be obtained from the Nuclear.Ru (Nuclear Site): http://www.nuclear.ru/rus/production/10/?from=180.

Table 1

Table 1. Detector BDKB-01R characteristics.

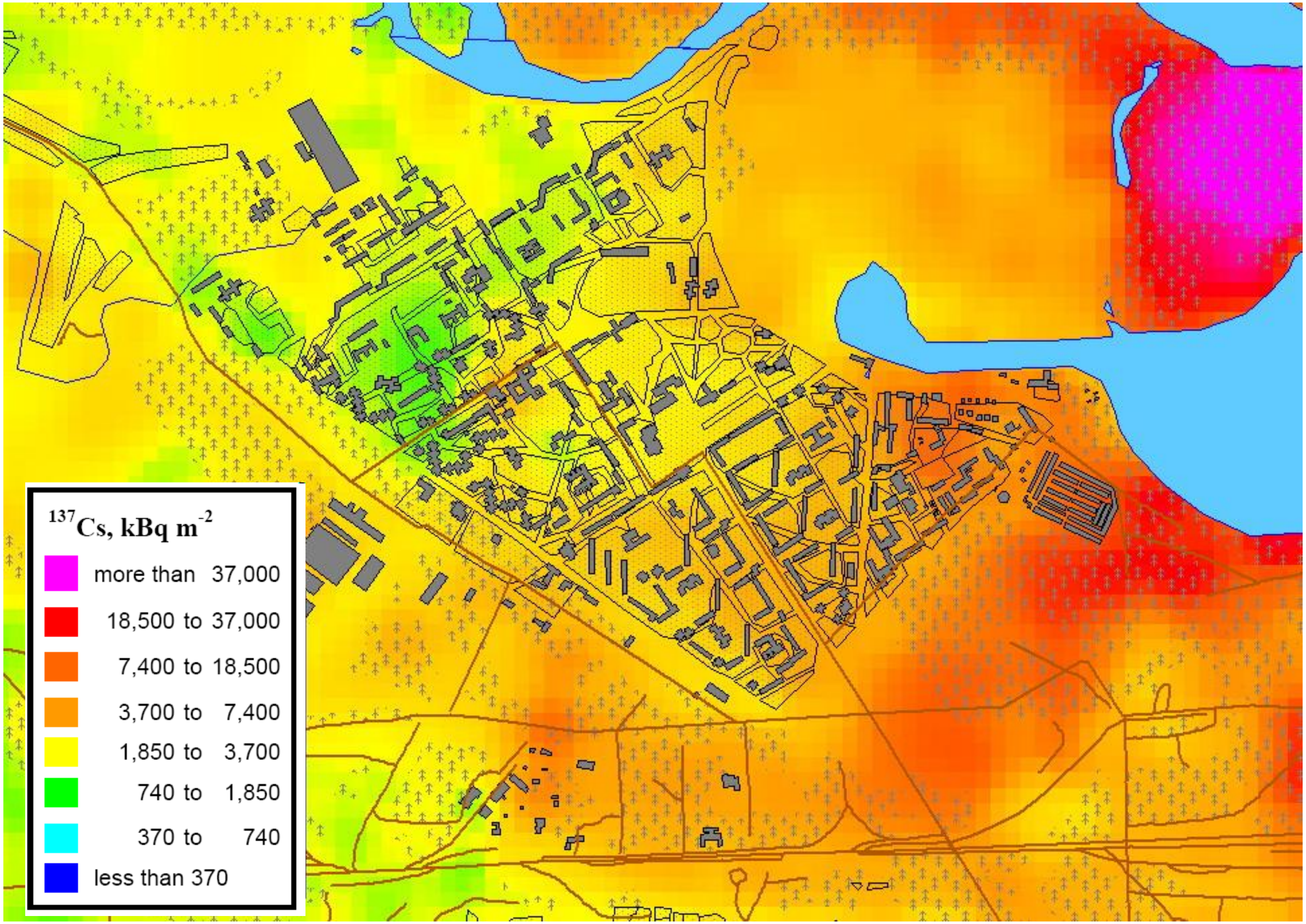
Type of radiation	Measured value	Measurements range	Power range for the measured radiation	Total error, %
Beta	Beta flux, particles cm^{-2} min	$1 – 10^5$	0.3 – 3 MeV of the maximum value of the beta spectrum energies	±20
Gamma	Equivalent dose rate, µSv h^{-1}	$0.1 – 10^4$	0.125 – 1.25 MeV	±20

Figure 1



Area of Measurements
Pripyat
N
Pripyat River
ChNPP Cooling Pond
2.7 km
Belarus
Ukraine
Chernobyl Nuclear Power Plant

Figure 2



^{137}Cs, kBq m^{-2}
more than 37,000
18,500 to 37,000
7,400 to 18,500
3,700 to 7,400
1,850 to 3,700
740 to 1,850
370 to 740
less than 370

Figure 3

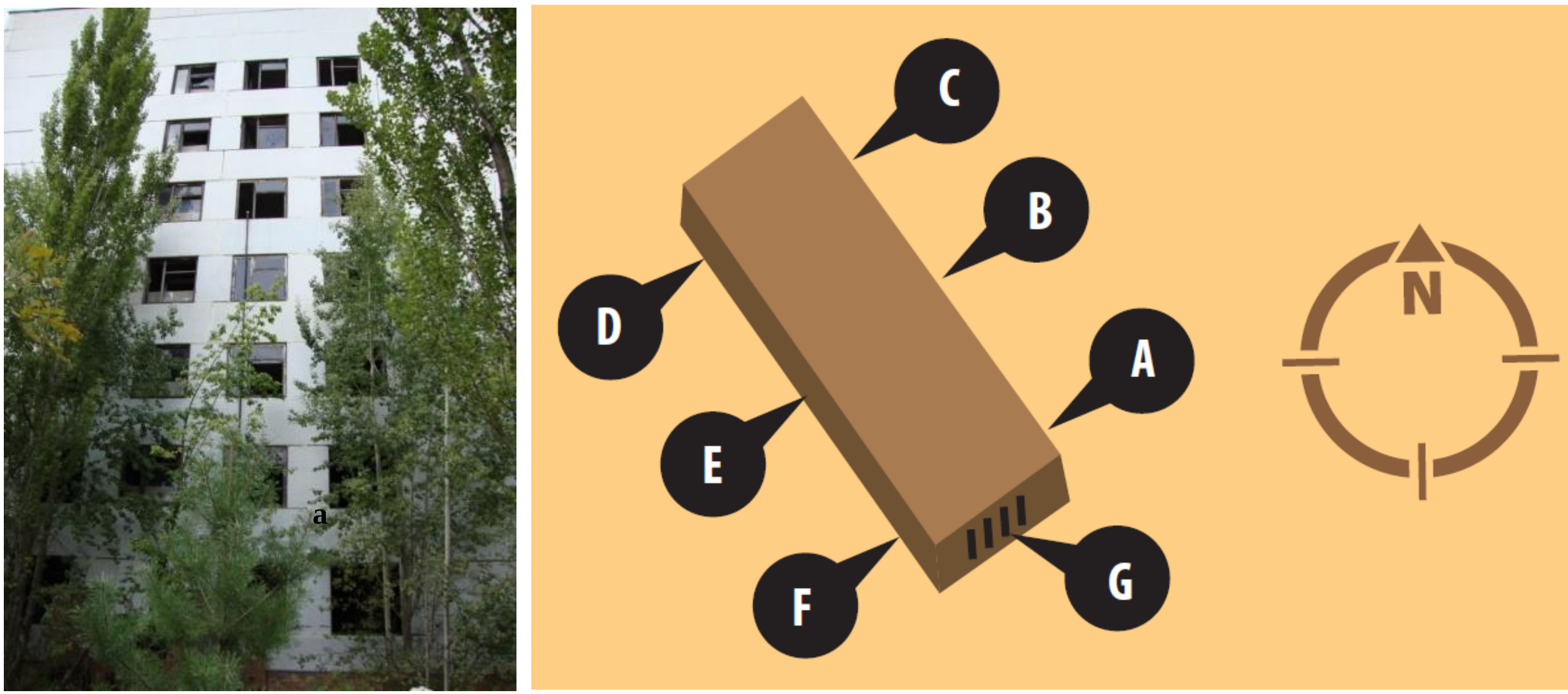


Figure 4

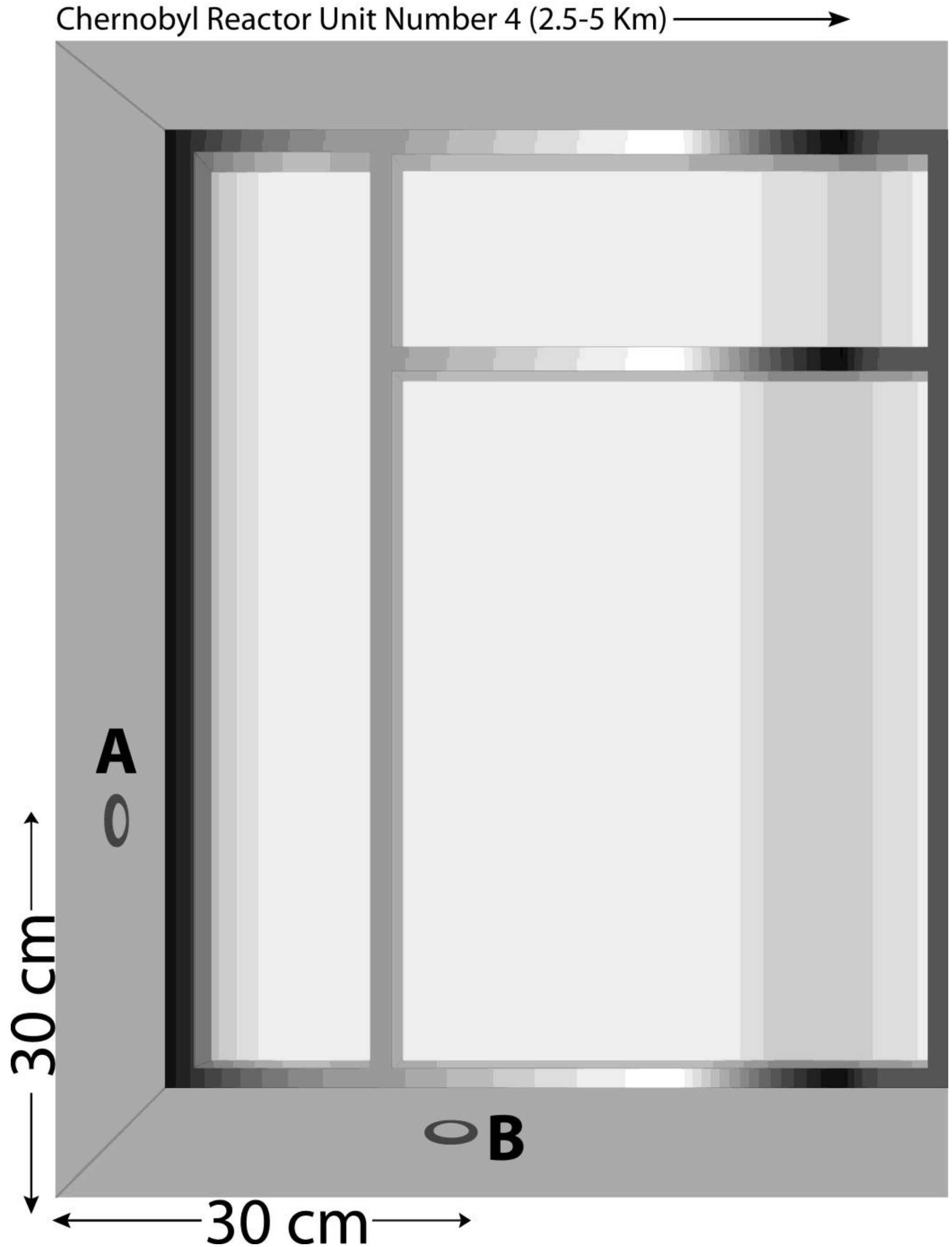
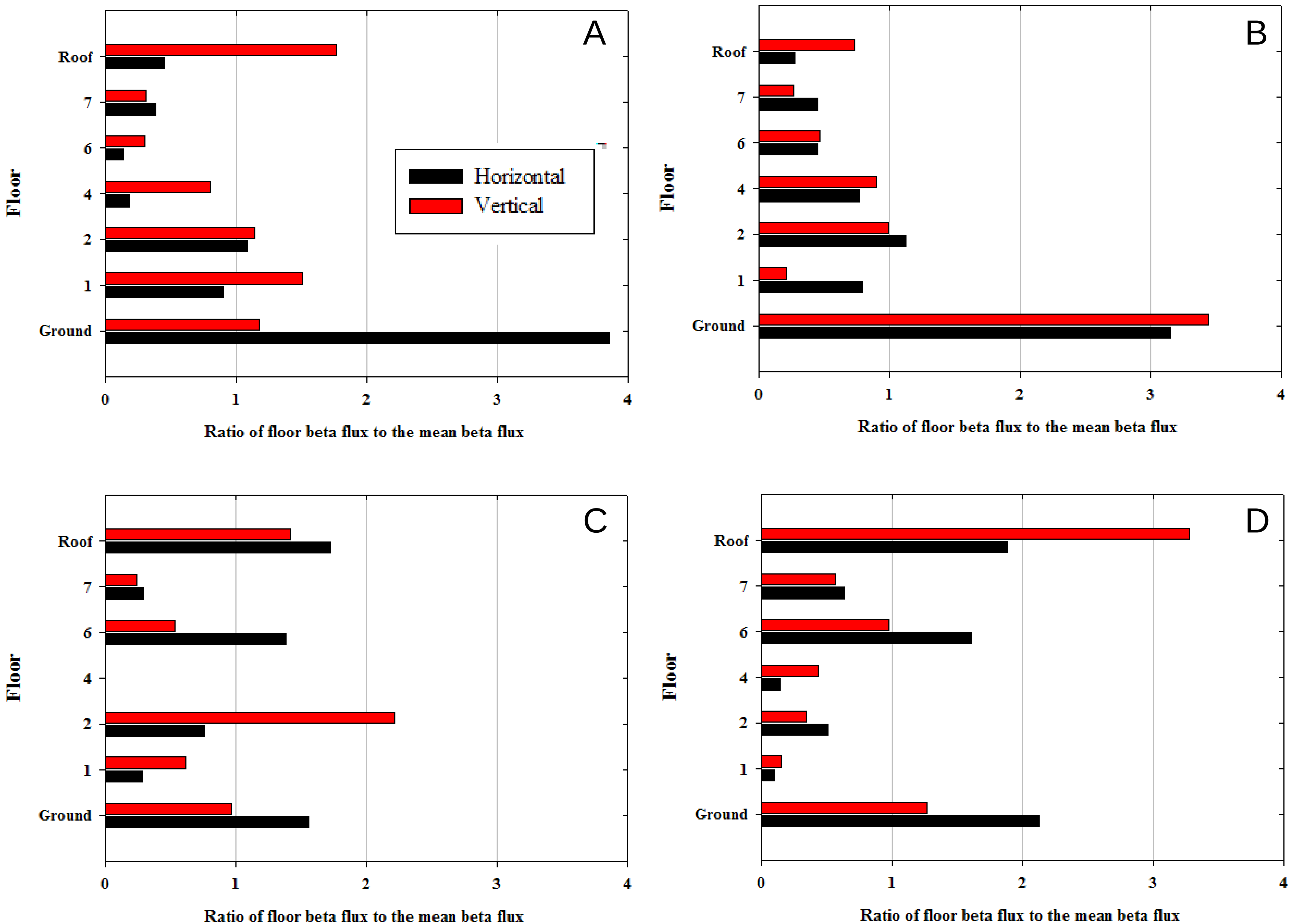
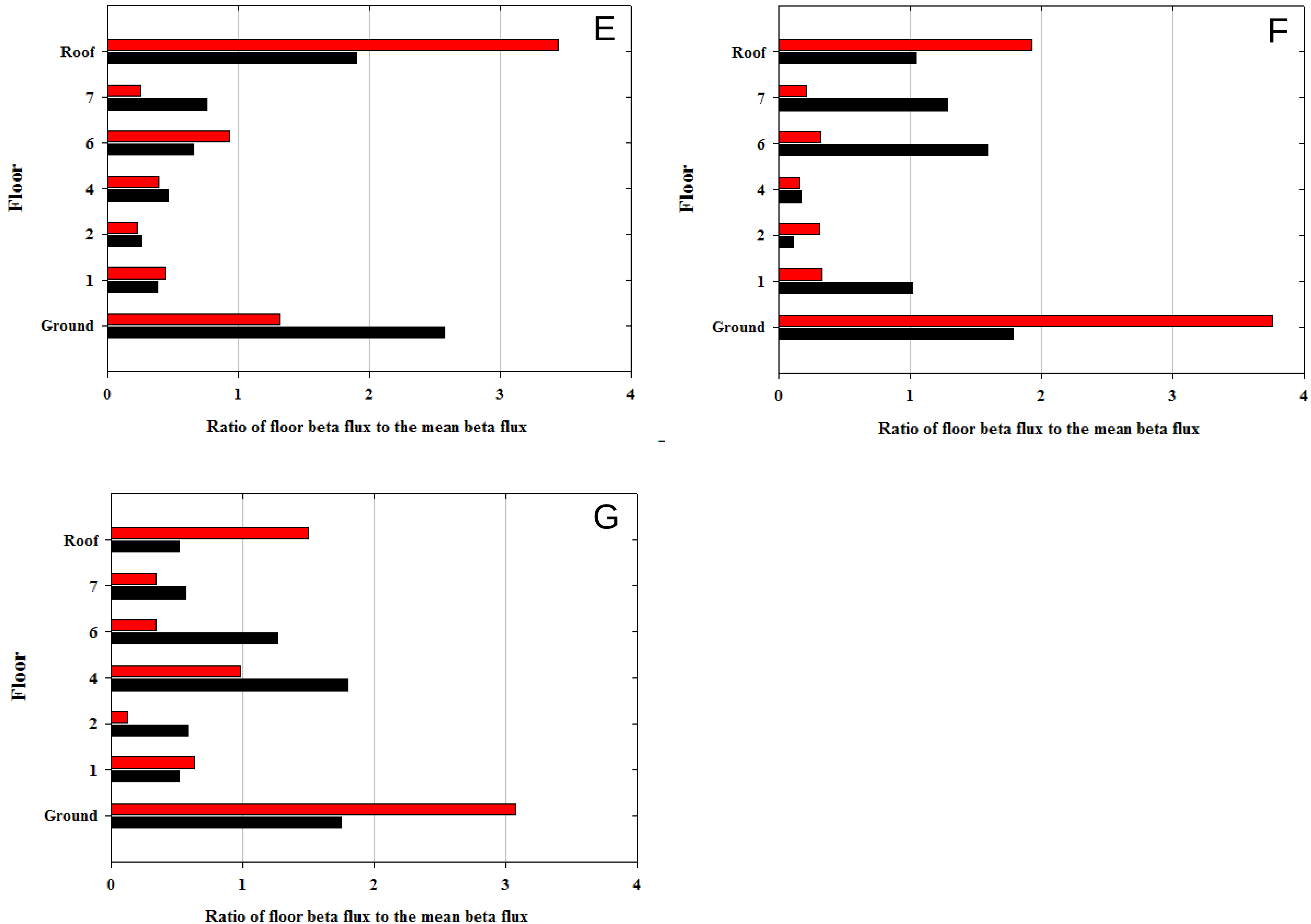


Figure 5


A
B
C
D
Horizontal
Vertical
Floor
Roof
7
6
4
2
1
Ground
0
1
2
3
4
Ratio of floor beta flux to the mean beta flux


E
Roof
7
6
4
2
1
Ground
Floor
0
1
2
3
4
Ratio of floor beta flux to the mean beta flux
F
Roof
7
6
4
2
1
Ground
Floor
0
1
2
3
4
Ratio of floor beta flux to the mean beta flux
G
Roof
7
6
4
2
1
Ground
Floor
0
1
2
3
4
Ratio of floor beta flux to the mean beta flux