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Investigations of radiation exposures in the aftermath of the Chernobyl accident

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Long-term assessment of the aftermath of the Chernobyl and Fukushima accidents deals with the study of radionuclide emissions and radiation exposure in heavily polluted regions.

A significant difference in the composition and nature of radionuclide emissions during accidents at nuclear power plants is considered in the study - a large-scale radioactive fallout transfer and precipitation over the USSR and Europe took place in Chernobyl due to the uncovered core of the reactor while at Fukushima a massive emission of inert gases occurred.

It is noted that based on the density of precipitation, the data indicating that the vital doses of ^{137}Cs remain significantly lower or within the range of natural radiation exposure were obtained. However, due to a short half-life (8.0 days) of ^{131}I, there are no available comprehensive measurements of ^{131}I exposure after the accident. It is noted that retrospective dosimetry of the effect of ^{131}I on the thyroid gland through ^{129}I with a half-life of 15.7 Ma allows to fill the gap in this issue.

^{137}Cs precipitation was analyzed by gamma spectrometry, ^{129}I was studied by accelerating mass spectrometry in soil samples from 60 places in zones II and III in the north of Ukraine and the thyroid gland radiation dose in the population.

Critical comparing of the results obtained with those of rare direct measurements of ^{131}I activity in the human thyroid gland reveal that the doses are at the lower limit. The actual radiation exposure in the contaminated regions of Northern Ukraine was considered by estimating the exposure dose in returnees in the village of Khrystynivka where 30 families live and consume locally produced products in the evacuated zone II, 75 km from the Chernobyl NPP.

The results show that the additional irradiation with ^{137}Cs the returnees received was low. The possibility of safe living in heavily polluted areas is noted. Under the normal way of life, the total radiation exposure of Khrystynivka village residents was within the natural radiation exposure range.

Key words: radioactive fallout, radiation exposure, radiation pollution, irradiation of returnees.

Problem statement and analysis of recent research. Acknowledging three decades of research on the consequences of the Chernobyl accident a short review is given on the accident, the releases of radionuclides and the radiation exposures in the highly contaminated regions. The Chernobyl accident has provided a wealth of information about the consequences of a nuclear reactor accident (UNSCEAR 2000, 2008, 2018). The past experiences provided heuristic guidelines to estimate the consequences of large scale contaminations with Cs-137, Sr-90 and actinides; e.g. Michel (2006) and were extremely helpful for fist estimates of the consequences of the Fukushima accident. In this presentation, I look back – after a general survey on the Chernobyl and Fukushima accidents – to our joint work with the State University of Agriculture and Ecology, Zhitomir, in particular to the collaboration with L.D. Romantschuk.

The reactor accidents at Chernobyl and Fukushima. The accidents at Chernobyl and Fukushima occurred 25 years ago on April 26, 1986 and March 11, 2011. At Chernobyl, a graphite-moderated, water-cooled pressure tube reactor without containment exploded. After an uncontrolled power excursion a graphite fire and melting of the core occurred as a consequence of design deficits and human malpractice. At Fukushima, 3 cores of water-moderated, water-cooled boiling water reactors with reactor pressure vessels and containments melted and 4 hydrogen explosions as well as multiple venting occurred as a consequence of design deficits and station blackout due to an earthquake and a tsunami.

At Chernobyl, there was no retention of radionuclides because of the uncovered reactor core. Large amounts ($5.3 \cdot 10^{18}$ Bq) of radionuclides were released depending on their volatility; Strontium-90 and Plutonium-isotopes remained mostly in the close proximity of the plant. Large-scale transport and fallout of radioactivity over the USSR and Europe happened. At Fukushima, many radionuclides were kept inside the reactors due to the suppression chambers and containments. Massive release of rare gases occurred. In addition, I-131 (> 10^{17} Bq) and ^{134,137}Cs (> 10^{16} Bq) were released into the atmosphere and the Pacific. ^{90}Sr and Pu-isotopes were not released in dose relevant amounts. Small-scale (about 20 %) fall-out occurred over Northern Japan; large-scale transport and fall-out happened mostly over the Pacific. At Chernobyl, about one order of magnitude more radioactivity was released than in Fukushima; both accidents having completely different compositions of radionuclide releases.

The radiological consequences of the Chernobyl accident were (UNSCEAR 2000, 2008, 2018): 134 first responders suffered from acute radiation syndrome; 28 of them died. A total of 114.511 persons were immediately evacuated. They received thyroid doses up to a few Sievert and effective doses up to a few times 10 Millisievert. Of more than 500.000 liquidators, about 300.000 persons received mean effective doses of 146 mSv in 1986, about 138.000 persons 96 mSv in 1987. The not evacuated population in the highly contaminated areas received the highest radiation exposures: thyroid doses up to some 10 Sieverts for children, 26.000 persons received effective doses of more than 100 mSv from long-lived radionuclides during 1986–2005.

At Fukushima (UNSCEAR 2013, 2021), no deterministic effects and no acute radiation syndrome occurred, neither in workers nor in the public. Early evacuation of about 80.000 persons was performed; later extended the evacuations to a total of 146.520 persons. The thyroid doses of 1.080 children from Kawamata – one of the most highly affected towns – remained below 200 mSv, for 95 % of the children below 50 mSv. The external radiation exposure during the first 4 months of 9.747 persons in Namie, Iitate and Kawamata was: 58 % below 2 mSv, 92 % below 5 mSv, 99 % below 10 mSv, maximum 23 mSv. The internal radiation exposure remained below 0,1 mSv/a (on the basis of foodstuff from October/November 2011); whole body measurements of 4.745 persons in Minami Soma between October and December 2011 showed 0,035 mSv/a – 0,070 mSv/a.

Lifetime doses in Fukushima city were estimated to remain below 20 mSv, external exposure being dominating. The predominant majority of the population of Eastern Japan received thyroid doses of children below 10 mSv and effective doses below 1mSv. In the metropolitan area of Tokyo thyroid doses of children were below 1 mSv and effective doses below 0,1 mSv. There was no significant radiation exposure in Hokkaido and Western Japan. Also the occupational exposure of the workers at Fukushima during and after the accident was comparably low. 171 workers received more than 100 mSv, 139 workers between 100 mSv – 150 mSv, 23 workers between 150 mSv – 200 mSv, 3 workers 200 mSv – 250 mSv, and 6 workers more than 250 mSv (309 mSv – 678 mSv).

Research results and discussion. Radiation exposures in Ukraine and elsewhere. General. A method to judge about the radiological consequences of the Chernobyl accident was developed in the former USSR. The method was based on a classification into 4 contamination zones. Table 1 shows the zones, the conservatively expected lifetime doses due to ^{137}C as well as the extent of the contamination in the various countries. Zone I is what later on was called the exclusion zone. This zone I also includes the areas which are highly contaminated with ^{90}Sr and Actinides and which will be excluded for a long time from human habitation. Zone II became the evacuated zone and zone III that of voluntary relocation. Zone IV was estimated to be of low radiological concern. This system of contamination zones was at that time in agreement with international recommendations for emergency situations.

The population that was not evacuated from the highly contaminated areas received the highest radiation exposures: thyroid doses up to some 10 Sieverts for children, 26.000 persons received effective doses of more than 100 mSv from long-lived radionuclides during 1986–2005 (UNSCEAR 2000).

In zone 2 of Ukraine 35 villages and towns with 30.908 inhabitants were immediately evacuated and 8 further settlements were evacuated between May 10 and May 28, 1986. In the course of the Perestroika, in the late 1980s, the people in the USSR for the first time obtained more detailed knowledge about the accident and its radiological consequences. This caused the public to demand protection standards based on an additional effec-

Table 1 – **Areas contaminated with ^{137}Cs and the definition of contamination zones according to the expected lifetime doses of a self-sustained rural population without countermeasures; without thyroid doses**

	Regions with ^{137}Cs deposition densities in km^2			
Zones	Zone 4: 37–185 kBq m^{-2}	Zone 3: 185–555 kBq m^{-2}	Zone 2: 555–1.480 kBq m^{-2}	Zone 1: 1.480–3.700 kBq m^{-2}
Expected lifetime dose	5–30 mSv	30–100 mSv	100–350 mSv	> 350 mSv
Russian Federation	49.800	5.700	2.100	300
Belarus	29.900	10.200	4.200	2.200
Ukraine	37.200	3.200	900	600
Western Europe	45.260	^{137}Cs deposition densities > 185 kBq m^{-2} exist only in small areas in Sweden near Gävle and in Austria near Salzburg. ^{137}Cs contains 2 - 4 kBq m^{-2} from global fall-out of atmospheric nuclear weapons explosions in the 1960ties.			

tive dose of 1 mSv per year, a limit which is worldwide only used for nuclear installations during normal operation but not for emergency situations. As a consequence, the inhabitants of 27 villages in Ukraine were resettled in zone II between 1989 and 2004 and those of 25 villages and towns in zone 3. These late resettlements were not reasonable from a radiological point of view, since the resettled people had already received the major share of the exposure from the accident and then, in addition, their lives were disrupted by the resettlement with severe social consequences. As a rule of thumb, the lifetime doses will be a factor of 2 or 3 higher than the dose one receives without countermeasures in the first year. For example, the doses during the period 1986 to 1995 make up 66±5 % of the total 70 years committed dose (table 2).

Based on the deposition densities reliable estimates of the expected lifetime doses can be made (Fig. 1). It turns out that the lifetime doses due to ^{137}Cs remain well below or within the range of the natural radiation exposure. This, however, does not hold true for the exclusion zone where high contaminations with ^{90}Sr and Actinides add to this exposure.

Retrospective dosimetry of ^{131}I exposure using ^{129}I. Regarding the health effects as a consequence of the Chernobyl accident in the general public, up to now no increase of solid tumors, leukemia, genetic defects and unfavorable pregnancy outcome was observed (UNSCEAR 2000, 2008, 2018). There was, however, an increase of other health problems for which a causal connection to radiation could not be found. They are estimated to be connected to the severe social consequence of the accident and the emergency measures. The latter also applies to Fukushima, where severe mental health consequences due to the emergency measures were observed.

But, 5 years after the accident a marked increase of thyroid cancer was observed in the former USSR in those which were aged less than 15 years at the time of the accident. Up to 1998, 1.036 cases of childhood thyroid cancer were observed and the increase is still going on. Up to 2005, about 4.000 cases and about 6.000 cases up to 2015 were observed. Until 2005, 15 of them passed away from thyroid cancer. These thyroid cancers were caused by the high exposures of the thyroids due to ^{131}I either by inhalation during the transition of the radioactive cloud or by ingestion of contaminated leafy vegetables and milk. Since no countermeasures were ordered such as staying in home and a ban the consumption of fresh vegetables and milk, the thyroid doses of the children were excessively high.

Table 2 – **Exposure of the population in contaminated regions with ^{137}Cs > 37 kBq m^{-2} during 1986 to 2005 without thyroid doses (UNSCEAR 2000)**

Region	Population	Mean individual effective dose in mSv			
		1986 – 1995			1986 – 2005
		external	internal	total	total
Belarus	1.880.612	5,1	2,9	8,0	9,8
Russian Federation	1.983.275	4,3	2,5	6,8	8,3
Ukraine	1.295.800	4,7	6,1	10,8	12,9

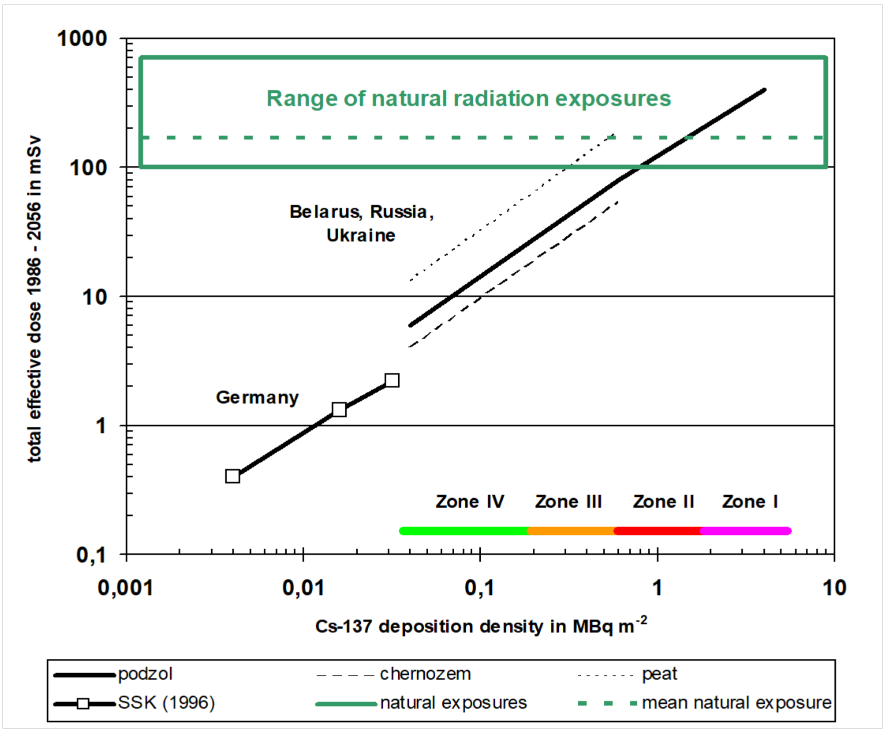

Fig. 1. **Average total effective 70-years dose (without thyroid doses) due to the Chernobyl accident in areas with ^{137}Cs Fallout of more than 37 kBq m^{-2} for a rural population without countermeasures.** (Michel 2006)

Since there is generally a lack of comprehensive measurements of the ^{131}I exposure after an accident due to the short half-life of 8,0 days of ^{131}I, the retrospective dosimetry of the ^{131}I thyroid exposure via ^{129}I with a half-life of 15,7 Ma offers an opportunity to fill the gap of knowledge. The retrospective dosimetry has gained large interest after the Fukushima accident where due to the consequences of the earth quake and the tsunami direct measurements of the thyroid exposure are rare and one has to rely for the estimation of thyroid doses on model calculations and on the retrospective dosimetry. In a joint project we have investigated the feasibility of this method in a large area of Northern Ukraine (Michel et al. 2005, 2015). The retrospective dosimetry of the ^{131}I thyroid exposure via ^{129}I is done via the formula

$$H_{\text{thyr}} = \left(D(^{129}\text{I}) - D_{\text{pre-Ch.}}(^{129}\text{I})\right) \cdot \frac{A_{131}}{A_{129}} \cdot DC_{131}$$

with H_{thyr} being the thyroid equivalent dose due to ^{131}I, $D(^{129}\text{I})$ the measured ^{129}I deposition density, $D_{\text{pre-Ch.}}(^{129}\text{I})$ = 44±24 mBq m^{-2} the pre-Chernobyl deposition, DC_{131} the aggregated dose factor for ^{131}I (Krajewski 1996). The ^{129}I/^{131}I isotopic ratio of the Chernobyl fall-out was 12 ± 3, i.e. A(131I)/A(129I) = 5,9 · 10^7. It has to be emphasized that the dose factor DC_{131} has to be derived from model calculations which need detailed knowledge about the habits of the population in question.

After an initial investigation of the feasibility of the method (Michel et al. 2005) we analyzed the deposition of ^{137}Cs by gamma-spectrometry and of ^{129}I by accelerator mass spectrometry in soil samples from 60 locations in zones II and III in Northern Ukraine and derived from them estimates of the thyroid doses received by the inhabitants (Michel et al. 2015). The results obtained for 5-years-old children are shown in Fig. 2. The doses were partially excessively high, up to 30 Gy. The doses could have been significantly lowered by the emergency measure “staying in house during the transition of the cloud” and ban of the consumption of leafy vegetables and of milk. But this was not done.

In a critical comparison of our results with the results of the rare direct measurements of ^{131}I activities in the human thyroids (Michel et al. 2015) we saw that the retrospective dosimetry gave dose estimates which were at the lower end of the observed doses. This depended mainly on the dose factor due to the lack of knowledge of the individual habits of the inhabitants. In conclusion, we saw that ^{129}I retrospective dosimetry is feasible. But it needs an adequate radioecological modeling which takes into account the actual exposure conditions. It is only the second quality compared to direct measurements after an accident.

Exposures of returnees into the evacuated zones. After the fall of the iron curtain, joint projects between Ukrainian and Western European scientists became possible. We started collaboration with the State University of Agriculture and Ecology at Zhitomir in the 1990ties. Our joint research on the consequences of the Chernobyl accident dealt with the inhabitants of areas with ^{137}Cs deposition densities of more than 37 kBq m^{-2}.The actual radiation exposures in the highly contaminated regions of Northern Ukraine were addressed by evaluating the exposures of returnees into the evacuated zone. The references below give a survey on our joint research projects with the State University of Agriculture and Ecology, Zhitomir. Besides Cs-137 also the exposure to Sr-90 and actinides was taken into account. We concentrated our work on Christinovka which is a typical village in the evacuated zone II, 75 km away from Chernobyl NPP, Narodici rayon. All inhabitants were evacuated in 1989/90. Since 1995, about 30 families returned to their homes. Except for bread, all foodstuffs are locally produced.

The deposition of ^{137}Cs, the ambient dose rates and the contamination of foodstuffs were analyzed beforehand (Beltz 2000, Botsch et al. 1999a, 1999b, 2000, Filß et al. 1998). However, it turned out that for reliable estimates of the exposure of the returnees we had to know more about their habits. In particular, it became clear that the ^{137}Cs in mushrooms dominated the internal exposure and that a reliable estimate of the consumed amounts were not possible. Moreover, the external exposure strongly depended on the time a person spend in the forests which were much higher contaminated than the open country side. Therefore, we equipped the inhabitants with personal dosemeters for the duration of an entire year and we organized measurements of the whole body activities of the inhabitants with a mobile body counter. The results of this investigations are summarized in Table 3 (Handl et al. 2003).

The results in table 3 clearly demonstrate that the additional exposure the returnees received from ^{137}Cs were small, both for those concerned of radiation with a cautious behavior and those with a normal behavior. However, we observed also two extreme cases. Person no. 18 spent a lot of time in the forests and lived mainly on potatoes and mushrooms. These habits caused a dose of more than 20 mSv in that year. His companion (no. 17) got also comparably high doses because of the particular life-style. These observations demonstrated that the feasibility to life safely in the highly contaminated zones depends on the personal behavior rather than on the mere deposition densities of ^{137}Cs. With normal behavior, the total radiation exposure of the inhabitants of Christinovka was below that in not-contaminated areas of Finland and should not be a matter of concern.

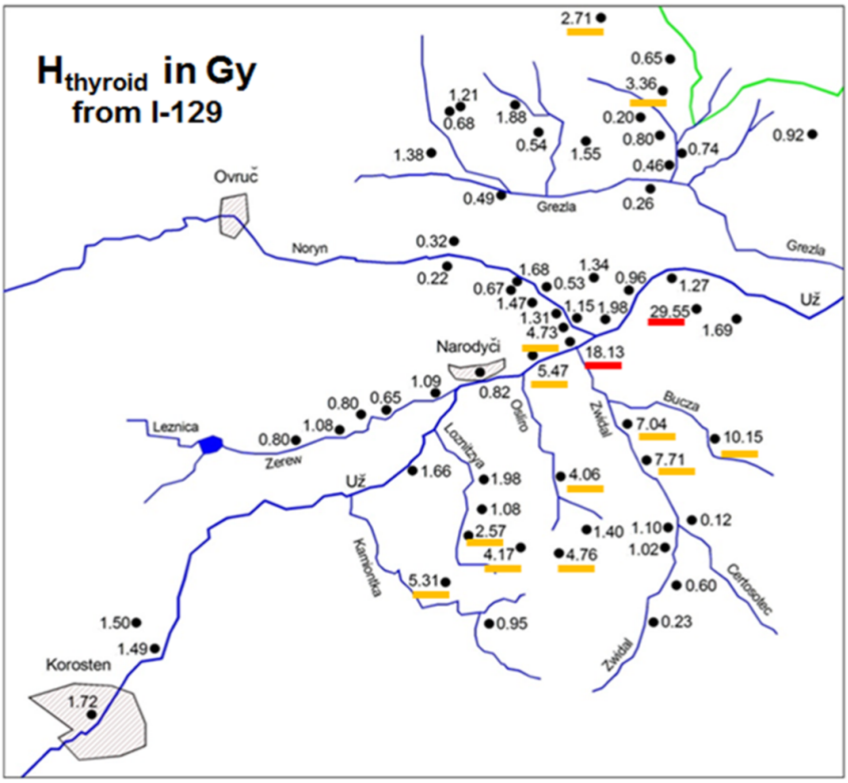

Fig. 2. **Thyroid doses of 5-years-old children derived by retrospective dosimetry.**

Table 3 – **External and internal exposure for different groups of the population of Christinovka 7/1997 to 7/1998**

	groups of inhabitants of Christinovka					
	concerned		normal	Extreme		total
type of exposure	no. 9	no. 10	nos. 1 - 16	no. 17	no. 18	nos. 1 - 18
external	0,8	1,1	$0,7 \times 1,3^{\pm 1}$	2,7	4,3	$0,8 \times 1,7^{\pm 1}$
internal	0,2	0,3	$0,3 \times 1,9^{\pm 1}$	10	17,3	$0,4 \times 3,4^{\pm 1}$
due to mushrooms	-	-	0,1	9,7	17	0,2
due to other food	0,2	0,3	0,2	0,3	0,3	0,2
total	1	1,4	$1,0 \times 1,3^{\pm 1}$	13	21,6	$1,3 \times 2,4^{\pm 1}$

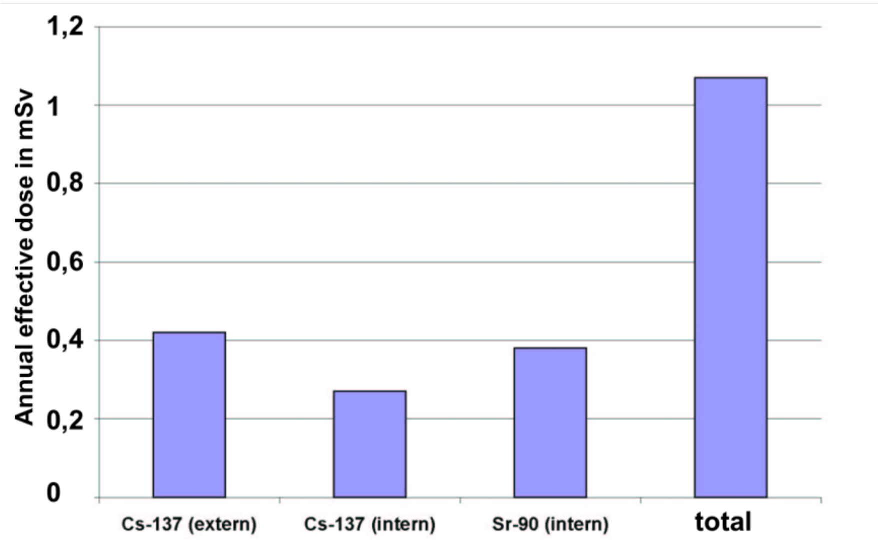

Fig. 3. **Radiation exposure in Christinovka 2002**

In later years, we developed methods for realistic assessments of the radiation exposure on the basis of environmental data and we extended our investigations to the exposure due to ^{90}Sr and actinides. In total, from 1996 to 2007 we investigated soil profiles of agricultural soils, plants, meat, fish, and other foodstuffs for ^{137}Cs, ^{90}Sr, ^{238}U, ^{235}U, ^{238}Pu, $^{239,240}Pu$, ^{241}Am, and ^{244}Cm. The results of these investigations in Christinovka for the year 2002 are shown in Fig. 3. While the exposure due to ^{90}Sr was not negligible, that due to the actinides was negligible (less than 2 Sv per year) even for smokers of self-grown tobacco. The latter received about 40 Sv per year more exposure due to actinide radioisotopes. In summary, the total exposure of the inhabitants in Christinovka is well within the range of worldwide natural radiation exposures and not a matter of concern. The open question about the way back to normality in zone 2 should soon be answered.

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Дослідження радіаційного впливу після аварії на Чорнобильській АЕС

Мішель Р., Романчук Л.Д.

Довгострокове оцінювання наслідків аварій на Чорнобильській АС та на Фукусімі пов'язане з вивченням викидів радіонуклідів і радіаційного опромінення в сильно забруднених регіонах.

Розглянуто істотну різницю в складі і характері викидів радіонуклідів під час аварій на атомних станціях – в Чорнобилі через непокриту активну зону реактора відбулося широкомасштабне перенесення і випадання радіоактивних опадів над СРСР і Європою; на Фукусімі стався масовий викид інертних газів.

Відзначено, що на основі щільності випадінь було отримано дані, які свідчать про те, що життєві дози ^{137}Cs залишаються значно нижче або в межах діапазону природного радіаційного опромінення. Однак через короткий період напіврозпаду ^{131}I, що становить 8,0 діб, відсутні комплексні вимірювання впливу ^{131}I після аварії. Зазначено, що ретроспективна дозиметрія впливу ^{131}I на щитовидну залозу через ^{129}I з періодом напіврозпаду 15,7 Ма дає змогу заповнити прогалину в цих знаннях.

Проаналізовано випадання ^{137}Cs за допомогою гама-спектрометрії та ^{129}I за допомогою прискорювальної мас-спектрометрії в зразках ґрунту з 60 місць у зонах II і III на півночі України і дози опромінення щитовидної залози, отриманого населенням.

За критичного порівняння отриманих даних з результатами рідкісних прямих вимірювань активності ^{131}I у щитовидній залозі людини доведено, що дози знаходяться на нижній межі. Фактичне радіаційне опромінення в забруднених регіонах Північної України було розглянуто оцінюванням опромінення репатріантів у селищі Христинівка в евакуйованій зоні II, за 75 км від Чорнобильської АЕС, де проживає 30 сімей, які вживають продукти місцевого виробництва.

За даними дослідження додаткове опромінення, отримане репатріантами, було невеликим від ^{137}Cs. Зазначено можливість безпечного життя в сильно забруднених районах. За нормального способу життя загальне радіаційне опромінення жителів Христинівки було в межах діапазону природного радіаційного опромінення.

Ключові слова: радіоактивні опади, радіаційне опромінення, радіаційне забруднення, опромінення репатріантів.

Исследования радиационного воздействия после аварии на Чернобыльской АЭС

Мишель Р., Романчук Л.Д.

Долгосрочная оценка последствий аварий на Чернобыльской АС и на Фукусиме связана с изучением выбросов радионуклидов и радиационного облучения в сильно загрязненных регионах.

Рассмотрена существенная разница в составе и характере выбросов радионуклидов во время аварий на атомных станциях – в Чернобыле из-за непокрытой активной зоны реактора были широкомасштабный перенос и выпадение радиоактивных осадков над СССР и Европой; на Фукусиме произошел массовый выброс инертных газов.

Отмечено, что на основе плотностей выпадений были получены данные, которые свидетельствуют о том, что жизненные дозы ^{137}Cs остаются значительно ниже или в пределах диапазона естественного радиационного облучения. Однако, из-за короткого периода полураспада ^{131}I, составляющего 8,0 суток, отсутствуют комплексные измерения воздействия ^{131}I после аварии. Указано, что ретроспективная дозиметрия воздействия ^{131}I на щитовидную железу через ^{129}I с периодом полураспада 15,7 Ма позволяет восполнить пробел в этих знаниях.

Проанализировано выпадение ^{137}Cs с помощью гамма-спектрометрии и ^{129}I с помощью ускорительной масс-спектрометрии в образцах почвы из 60 мест в зонах II и III на севере Украины и дозы облучения щитовидной железы, полученного населением.

При критическом сравнении полученных данных с результатами редких прямых измерений активности ^{131}I в щитовидной железе человека доказано, что дозы находятся на нижнем пределе. Фактическое радиационное облучение в загрязненных регионах Северной Украины было рассмотрено путем оценки облучения репатриантов в поселке Кристиновка в эвакуированной зоне II, в 75 км от Чернобыльской АЭС, где проживает 30 семей, которые употребляют продукты местного производства.

По данным исследования дополнительное облучение, полученное репатриантами, было небольшим от ^{137}Cs. Как итог, можно не исключать возможность безопасной жизни в сильно загрязненных районах. При нормальном образе жизни общее радиационное облучение жителей Кристиновки было в пределах диапазона естественного радиационного облучения.

Ключевые слова: радиоактивные осадки, радиационное облучение, радиационное загрязнение, облучение репатриантов.

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