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LONG-TERM PROGRAMME OF BIOPHYSICAL MONITORING OF THE PERSONNEL INVOLVED IN THE CONSTRUCTION OF THE NEW SAFE CONFINEMENT

The international Shelter Implementation Plan (SIP) foresees a step-by-step transformation of the Chornobyl site into the safe condition. The New Safe Confinement (NSC), is an unprecedented 108-meter tall structure over the destroyed Unit 4 of the Chernobyl Nuclear Power Plant, and is a central element of SIP. Many workers involved in SIP may have a direct contact with fragments of the irradiated fuel, fuel-containing aerosols, and other contaminated material at the Chornobyl industrial site. Isotopes of plutonium, americium, strontium, and cesium are dominating in internal exposure of SIP workers. The safety of workers is a high priority of SIP. Starting from 2004 the Ukrainian Radiation Protection Institute (RPI) is performing a large-scale Internal Dosimetry Program as an integral part of SIP. Pu contents in fecal and urine samples and the whole-body counters' (WBC) data and are the main source of the quantitative data used for the dose assessment. The RPI radiochemical laboratories in Kyiv and at the Chornobyl site employed the standard radiochemical technique and equipped with ninety six alpha-spectrometers. The range of WBCs includes the scanning low-background WBC, four Canberra FastScan WBCs, and four chair-type WBCs. The car-borne WBC is located in Kiev and reserved for the emergency purposes. As on September 2017 the Internal Dosimetry Program has covered more than 17 000 workers, which undergone 1 230 000 measurements of ^{137}Cs on WBCs, 87 000 measurements of $^{239+240}$Pu contents in fecal samples and 4 400 measurements of $^{239+240}$Pu contents in urine samples. Such a large-scale programme ensured a reliable monitoring of intakes of the insoluble radioactive material.

Keywords: Shelter Implementation Plan, new safe confinement, internal dosimetry program.

Introduction

The paper describes how the programme of individual monitoring of internal exposure at the «Ukryttya» object («Shelter» object) was designed. The main dose-forming factors of internal exposure at the «Ukryttya» object are intakes of radionuclides of transuranium elements, ^{90}Sr, ^{137}Cs. During designing of programme of individual monitoring of internal exposure the contribution of each radionuclide was estimated for different types of works and intake paths.

The works for construction of New Safe Confinement are carried out at the «Ukryttya» object and the local area. The works were performed in conditions of radionuclide contamination, formed during Chornobyl accident.

Radiation situation at the «Ukryttya» object

The main working mode is a shift work (up to 10 shifts per year). Duration of 'standard' shift is 15 days. Ukrainian sanitary legislation requires detection 1 mSv of internal dose. This requirement leads to the necessity to detect 0.1 mSv during the 'standard' shift.

For purposes of individual monitoring of internal exposure all works which are performed at the «Ukryttya» object were grouped in to 5 types:

type A comprising works with thermal or chemical impacts on contaminated constructions or fuel-containing masses in the «Ukryttya» object (e.g. welding);

type B including works with a perforation and drilling of contaminated constructions or fuel-containing masses in the «Ukryttya» object with the help of hand drills and drilling devices;

type C comprising works with an application of abrasive cutting of metal constructions in the «Ukryttya» object;

type D including all works not ascribed to A-C types, except works performed at low levels of ionizing radiation in the «Ukryttya» object (for example, scaffold assembly, removal of concrete beadings etc. relate to type D);

type E comprising all works not ascribed to A-D types.

Such categorization was the result of preliminary investigation and monitoring at the «Ukryttya» object.

The main dose-forming factors of internal exposure are intakes of ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, which are radionuclides of transuranium elements (TUE), and ^{90}Sr, ^{137}Cs. Each type of work is characterized by relative radionuclide content in contamination and aerosols parameters (types of materials and AMAD).

Table 1. **Relative content of radionuclides in aerosols at the «Ukryttya» object, %**

Radionuclide		Type of works			
		A	D	B, C	E
^{90}Sr		13.0		17.6	21.9
^{137}Cs	condensed form	49.3	16.4	15.2	14.0
	fuel form	32.9	65.8	60.8	56.0
^{238}Pu		0.10		0.13	0.16
^{239}Pu + ^{240}Pu		0.22		0.29	0.36
^{241}Pu		4.20		5.60	7.02
^{241}Am		0.28		0.38	0.46

The fuel matrix (with density ~9 $g \cdot cm^{-3}$) is the basis of aerosols of the «Ukryttya» object, so type of material S is used for all radionuclides. However ^{137}Cs is observed at the «Ukryttya» object in condensation form which is described by type of material F. Relative radionuclide contents are similar for all types of works excluding type A. Due to the thermal or chemical impacts there is an elevated content of ^{137}Cs in condensed form during such works.

Most of works can be characterized by large-size aerosols (AMAD 7 μm for types B and E, or 10 μm for types C and D). The bimodal size distribution is observed during works of type A. 60 % of activity is associated with AMAD 0.3 μm, 40 % is associated with AMAD 10 μm.

Rationale for methods of individual monitoring of internal exposure

Determination of significance of radionuclides

For the organization of individual monitoring of internal exposure at the «Ukryttya» object there were identified radionuclides, for which applicable monitoring methods allow to produce the most reliable estimates of the internal doses.

Calculations of radionuclide contribution to total internal dose were carried out. The aerosols of the «Ukryttya» object have greater density than reference aerosols (9 $g \cdot cm^{-3}$ instead of 3 $g \cdot cm^{-3}$), so computer code IDSS (Internal Dosimetry Support System) [1] based on the ICRP models was used for calculation. Summary of results of the specified calculations for all types of works are shown in Table 2.

Table 2. **Contribution to internal doses formed during all types of works, %**

Radionuclide	Inhalation			Ingestion		
	Minimum	Maximum	Average	Minimum	Maximum	Average
^{90}Sr	9.4	15.3	10.9	3.8	10.0	7.6
^{137}Cs	3.4	15.6	9.8	46.0	78.9	58.8
^{238}Pu	12.0	13.3	12.7	2.5	6.5	4.9
$^{239+240}$Pu	25.1	27.7	26.8	6.1	15.5	11.9
^{241}Pu	3.3	5.6	3.9	2.2	5.7	4.3
^{241}Am	34.0	37.8	36.0	6.4	16.3	12.5
Alpha-emitting TUE, total	71.0	78.8	75.4	15.0	38.2	29.3

The contribution of alpha-emitting TUE radionuclides to the total dose is from 71 to 79 % (for the inhalation).

Ingestion is not a typical intake for workers, but there is a possibility of swallowing of small fragments, licking off etc. The most significant contribution to the total dose after the ingestion is formed by ^{137}Cs (up to 79 %) and alpha-emitting radionuclides (from 15 to 38 %). Despite small content of TUE in radionuclide composition their contribution to total dose is significant even for ingestion.

General comparison of monitoring types

The following types of monitoring were analysed for their possible applicability for purposes of individual monitoring of internal exposure:

direct biophysical measurements (*in vivo* measurements) – measurements of ^{137}Cs or ^{241}Am content in lungs or whole body;

indirect biophysical measurements (*in vitro* measurements) – measurements of Pu radionuclides content in fecal and urine bioassay samples;

air monitoring.

Each type of monitoring has advantages and disadvantages as well. Some of them are well known, others are specific for the «Ukryttya» object.

The main advantages of measurements on whole body counter (WBC) are their immediacy and maximal ^{137}Cs content in radionuclide composition of the «Ukryttya» object.

However WBC measurements have problematical sides:

contribution of ^{137}Cs to the total dose is maximal only for the ingestion but not for the inhalation therefore there is a significant influence of ^{137}Cs: TUE variability on the total internal dose;

^{137}Cs accumulation in a body can be formed by an intake with foodstuffs contaminated by “Chornobyl fallout”.

Bioassay measurements have advantages that are specific for the «Ukryttya» object:

TUE contribution to the total internal dose is maximal for the inhalation (influence of ^{137}Cs:TUE variability on the total dose is insignificant);

TUE content in a body (and excretion from a body) formed by an intake with foodstuffs contaminated by “Chornobyl fallout” is insignificant.

Time from the sampling to the result during numerous *in vitro* measurements is from 3 to 4 weeks. Delayed decision making is a well known disadvantage of bioassay measurements.

The main advantage of the air monitoring is a possibility to obtain an actual data about aerosol characteristics at workplaces (concentrations, aerosol size distribution). Actually the reference data for 5 types of works (see Table 1) were obtained from the result of the air monitoring.

There are some disadvantages of the air monitoring, which complicate conversion from concentration in workplace air to concentration in inhaled air:

significant variability of aerosol concentration at workplaces;

inherent variability of protection coefficients for normally operating individual respiratory protection equipment (IRPE);

inherent variability of protection coefficients for normally operating IRPE;

random impairments in IRPE obturation and slippage of fine-dispersed aerosol particles;

aerosol dispersivity in the under-mask space can significantly variate in relation to characteristics and obturation coefficients of IRPE.

Numerical comparison of applicability of monitoring types

Procedures for the interpretation of measurement results are important not only at the interpretation stage. Understanding of these procedures is very useful at the design stage of the individual monitoring programme. The ICRP 78 publication and ‘dose per unit content’ (DPUC) conception [2] were used. DPUC function $z(t)$ is defined as a ratio of the effective dose per unit intake e to the retention (or daily excretion) function $R(t)$:

$$z(t) = e \,/\, R(t). \quad (1)$$

DPUC function is equal to the total expected effective dose of internal exposure corresponding to 1 Bq content of controlled radionuclide in lungs/whole body (or in daily faeces/urine sample) in case of a single intake of the radionuclide for the time t before the measurement (or bioassay sampling).

The one of key terms in individual monitoring of internal exposure is a ‘minimal detectable dose’ (MDD). MDD(t) is a maximal total expected effective dose of internal exposure, which can be obtained by worker and cannot be detected by monitoring procedures with t periodicity. MDD could be defined as follows:

$$\mathrm{MDD}(t) = z(t) \cdot \mathrm{MDA}. \quad (2)$$

Tables 3 – 5 show MDD functions for discussed methods of individual monitoring.

Calculated MDD values for WBC measurements are based on following MDA values: 500 Bq for ^{137}Cs, and 20 Bq for ^{241}Am. It should be noted, that specified MDA could be achieved by use of significantly different equipment and measurement time. MDA 500 Bq of ^{137}Cs content could be reached by use of WBC at the Sanitary lock of the «Ukryttya» object (duration of measurement is 3 minutes). MDA 20 Bq of ^{241}Am content in lungs could be reached by use of expert WBC for 15 minutes measurement duration.

Table 3 shows that monitoring of ^{137}Cs in the whole body could be acceptable in consideration the ingestion intake only.

Table 3. **MDD(*t*) for monitoring of ^{137}Cs content (in whole body and lungs) and ^{241}Am content (in lungs), mSv**

Time after intake, days	^{137}Cs			^{241}Am
	Whole body		Lungs	Lungs
	Inhalation	Ingestion	Inhalation	Inhalation
0*	0.61	–	0.61	–
1	0.76	0.007	2.0	5.1
2	0.90	0.009	2.5	6.3
4	1.0	0.011	2.8	7.2
7	1.1	0.013	2.9	7.6
15	1.2	0.013	3.1	8.1
30	1.3	0.015	3.5	9.0
60	1.6	0.018	4.1	10
90	1.8	0.022	4.5	12

*Time after intake '0 days' means, that measurement is performed immediately after the intake.

Tables 4 – 5 show MDD functions for indirect biophysical measurements based on all types of works (A – E). MDD values for bioassay measurements are based on following MDA values: 0.45 mBq for fecal sample (duration of measurement is 2 days), and 0.25 mBq for urine sample (duration of measurement is 6 days).

Analysis of $^{239+240}$Pu content in fecal samples can be selected as an appropriate method for a monitoring assuming that the inhalation is a main pathway. Control of $^{239+240}$Pu content in urine samples has not sufficient sensitivity. However, analysis of $^{239+240}$Pu content in bioassay samples is not acceptable in considering the ingestion (Table 5).

Table 4. **MDD(*t*) for inhalation intake (analysis of $^{239+240}$Pu content in bioassay samples), mSv**

Time after intake, days		Minimum	Maximum	Average
Faeces	7	0.005	0.015	0.008
	15	0.029	0.038	0.036
	30	0.041	0.055	0.051
	60	0.074	0.11	0.10
	90	0.13	0.20	0.18
	180	0.35	0.64	0.55
Urine	7	32	47	38
	15	60	70	65
	30	61	78	72
	60	61	83	77

Table 5. **MDD(*t*) for ingestion intake (analysis of $^{239+240}$Pu content in bioassay samples), mSv**

Time after intake, days		Minimum	Maximum	Average
Faeces	7	$1.7\cdot10^{-4}$	$4.2\cdot10^{-4}$	$2.4\cdot10^{-4}$
	15	0.48	1.2	0.69
	30	37	92	53
Urine	7	1.4	3.5	2.0
	15	4.7	12	6.8
	30	6.3	16	9.1

Conclusion on the applicability of monitoring types

Results of comparisons of monitoring types lead to the following conclusions:

monitoring of $^{239+240}$Pu content in fecal samples gives a possibility to detect the inhalation intakes formed annual effective internal doses which are not exceeded 1 mSv;

considering ingestion intakes, monitoring of $^{239+240}$Pu content in fecal samples is not sufficient. The daily monitoring of ^{137}Cs content on WBC makes possible to detect such events of ingestion intakes;

data of the air monitoring could be used as an addition to *in vitro* and *in vivo* measurements allowing to specify parameters of possible intake (type, date etc.)

Decision making criteria

As a result of the described analysis, the decision making criteria for individual monitoring of internal exposure were established. Criteria values are based on the 'standard' shift duration and reference type of works characteristics (see Table 1).

Derived investigation level (initiation the Special monitoring) was established as elevation on 1.5 mBq of $^{239+240}$Pu content in a daily fecal sample during pre-shift monitoring. Such elevation (on each shift during 1 year) as a result of inhalation intake during previous shift corresponds to 1 mSv of internal exposure.

Two levels for elevation of ^{137}Cs contents in whole body during working day (daily monitoring) were specified:

elevation on 600 Bq is a level of initiation the intra-shift monitoring (collecting of an additional fecal sample); such elevation during each working day in 1 year corresponds to 1 mSv of internal exposure due to the ingestion;

elevation on 2.5 kBq during a working day is a derived investigation level (initiation the Special monitoring); such elevation during a working day corresponds to 1 mSv of internal exposure due to the inhalation.

Summary on individual monitoring of internal exposure at the «Ukryttya» object

The main sources of the information are used for dose assessment for the personnel during works at the «Ukryttya» object:

$^{239+240}$Pu contents in fecal samples;

$^{239+240}$Pu contents in urine samples (Special monitoring);

^{241}Am in lungs (Special and Check-out monitoring);

^{137}Cs in whole body.

The following additional sources are used for the specification of possible date and type of intakes:

unified admission orders (date, duration and type of works);

operative dosimeters (date, time and duration of works);

personal and collective air samplers (total α-, β-activities);

impactors (total α-, β-activities, AMAD);

nose swabs (total α-, β-activities).

The specialized software IMIE (Individual Monitoring of Internal Exposure) [3] is used for dose calculation.

A small summary on individual monitoring of internal exposure of the personnel during works at the «Ukryttya» object for 12 years:

87 000 measurements of $^{239+240}$Pu contents in fecal samples;

4 400 measurements of $^{239+240}$Pu contents in urine samples;

4 400 measurements of ^{241}Am in lungs;

1 230 000 measurements of ^{137}Cs in whole body;

320 000 measurements of α-, β-activities in nose swabs.

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ДОВГОСТРОКОВА ПРОГРАМА БІОФІЗИЧНОГО КОНТРОЛЮ ПЕРСОНАЛУ, ЗАЛУЧЕНОГО ДО ПОБУДОВИ НОВОГО БЕЗПЕЧНОГО КОНФАЙНМЕНТА

У міжнародному Плані здійснення заходів (ПЗЗ) передбачається поетапне перетворення чорнобильського майданчика у безпечний стан. Новий безпечний конфайнмент є безпрецедентною структурою заввишки 108 м над зруйнованим 4-м блоком ЧАЕС, він є центральним елементом ПЗЗ. Багато працівників, залучених у ПЗЗ, можуть мати прямий контакт із фрагментами опроміненого палива, паливовмісними аерозолями та іншими забрудненими матеріалами на промисловому майданчику в Чорнобилі. Ізотопи плутонію, америцію, стронцію і цезію домінують у внутрішньому опроміненні працівників ПЗЗ. Безпека працівників має високий пріоритет у ПЗЗ. Починаючи з 2004 р., Науково-дослідний інститут радіаційного захисту АТН України (ІРЗ) здійснює великомасштабну програму дозиметрії внутрішнього опромінення як невід'ємну частину ПЗЗ. Дані вмісту плутонію у пробах калу і сечі та лічильників випромінювань людини (ЛВЛ) і основним джерелом кількісних даних, що використовуються для оцінки дози. Радіохімічні лабораторії ІРЗ у Києві і на майданчику в Чорнобилі використовували стандартну радіохімічну методику, вони оснащені 96 альфа-спектрометрами. Номенклатура ЛВЛ включає в себе скануючий низькофоновий ЛВЛ, чотири ЛВЛ Canberra FastScan і чотири ЛВЛ типу "крісло". Мобільний ЛВЛ розташований у Києві і зарезервований для надзвичайних цілей. Станом на вересень 2017 р. рамками програми дозиметрії внутрішнього опромінення було охоплено понад 17 000 працівників, які пройшли 1 230 000 вимірювань ^{137}Cs на ЛВЛ, 87 000 вимірювань вмісту $^{239+240}$Pu у пробах калу і 4 400 вимірювань вмісту $^{239+240}$Pu у пробах сечі. Така великомасштабна програма забезпечила надійний контроль надходжень нерозчинного радіоактивного матеріалу.

Ключові слова: план здійснення заходів, новий безпечний конфайнмент, програма дозиметрії внутрішнього опромінення.

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ДОЛГОСРОЧНАЯ ПРОГРАММА БИОФИЗИЧЕСКОГО КОНТРОЛЯ ПЕРСОНАЛА, ПРИВЛЕЧЕННОГО К СТРОИТЕЛЬСТВУ НОВОГО БЕЗОПАСНОГО КОНФАЙНМЕНТА

В международном Плане осуществления мероприятий (ПОМ) предусматривается поэтапное преобразование чернобыльской площадки в безопасное состояние. Новый безопасный конфайнмент – это беспрецедентная структура высотой 108 м над разрушенным 4-м блоком ЧАЭС, он является центральным элементом ПОМ. Многие работники, вовлеченные в ПОМ, могут иметь прямой контакт с фрагментами облученного топлива, топливосодержащими аэрозолями и другими загрязненными материалами на промышленной площадке в Чернобыле. Изотопы плутония, америция, стронция и цезия доминируют во внутреннем облучении работников ПОМ. Безопасность работников имеет высокий приоритет в ПОМ. Начиная с 2004 г., Научно-исследовательский институт радиационной защиты АТН Украины (ИРЗ) осуществляет крупномасштабную программу дозиметрии внутреннего облучения как неотъемлемую часть ПОМ. Данные содержания плутония в пробах кала и мочи, а также счетчиков излучений человека (СИЧ) являются основным источником количественных данных, используемых для оценки дозы. Радиохимические лаборатории ИРЗ в Киеве и на площадке в Чернобыле использовали стандартную радиохимическую методику, они оснащены 96 альфа-спектрометрами. Номенклатура СИЧ включает в себя сканирующий низкофоновый СИЧ, четыре СИЧ Canberra FastScan и четыре СИЧ типа "кресло". Мобильный СИЧ расположен в Киеве и зарезервирован для чрезвычайных целей. По состоянию на сентябрь 2017 г. в рамках программы дозиметрии внутреннего облучения было охвачено более 17 000 работников, которые прошли 1 230 000 измерений ^{137}Cs на СИЧ, 87 000 измерений содержания $^{239+240}$Pu в пробах кала и 4 400 измерений содержания $^{239+240}$Pu в пробах мочи. Такая крупномасштабная программа обеспечила надежный контроль поступлений нерастворимого радиоактивного материала.

Ключевые слова: план осуществления мероприятий, новый безопасный конфайнмент, программа дозиметрии внутреннего облучения.

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