Internal dose assessment in occupational unexpected exposure to Xe-133 and Xe-135

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Abstract. Following an unexpected exposure to high concentration of noble gases in which a reactor's worker was immersed during some minutes, internal dose assessment was required although the readings of the personal dosimeter were not significant. This requirement arose as a result of having obtained positive values of Xe-133 and Xe-135 in the thorax monitoring performed on the worker from a few hours to several days after the event. As the dose estimation methodology for these noble gases considers only external exposure, the requirement of internal dose evaluation was a challenge since no biokinetic models or dose coefficients of reference for occupational intake of these isotopes were available, in addition to the need for a rapid result of the dose estimation.
The intakes of the xenon isotopes were estimated from the reconstructed concentration of gases at the time of the event. Using the thorax measurements and the estimated intakes, it was observed that the measurements of internally deposited xenon were reasonably consistent with the behaviour of retained xenon in systemic tissues mainly in fat, observed in subjects and in model predictions found in literature. The Xe-133 dose factors recommended by ICRP 128 for patients treated with this radionuclide by re-inhalation of the gas for 10 minutes were considered for this scenario. For taking into account the dose contribution for Xe-135 inhalation, MIRD methodology was implemented. Additionally, positive results of HTO and I-131 in urine bioassays were evaluated using the biokinetic models recommended for the worker, under the assumption of acute inhalation and no contribution from previous intakes of these radionuclides. It was estimated a value of the committed effective dose for inhalation of Xe-133 and Xe-135 of ~0.2 mSv, and considering the contribution of HTO and I-131, it was obtained a total committed effective dose of ~0.3 mSv.

KEYWORDS: committed effective dose, xenon, unexpected exposure

1 INTRODUCTION

The xenon isotopes can be produced as fission products during reactors operations and are considered in the group of the least radiotoxic nuclides in internal exposure scenarios [1]. The international recommendations and national standards [2, 3, 4] point out that the external radiation dominates their occupational exposure and provide cloud immersion dose coefficients ($Sv.Bq^{-1}$ per $Bq.m^{-3}$) that mainly arise from external irradiation and assume that the doses from the absorbed inert gases are negligible.

Because the dose estimation methodology for these noble gases considers only external exposure [2, 3, 4], the need of an internal dose estimation following an unexpected exposure to high concentration of noble gases implies a challenge to internal dosimetry services to perform it without biokinetic models or dose coefficients of reference for occupational intake of these isotopes.

This work describes the actions and the methodology implemented to estimate the total committed effective dose in a reactor's worker who was immersed for some minutes in a cloud of high concentration of gases, despite the worker's personal dosimeter-readings had not been significant. The chronological order of actions to reconstruct the airborne concentration, the intake and the committed effective dose are presented. This work also describes the methodologies implemented to estimate the contribution to the total effective dose from the internal exposure to Xe-133, Xe-135, HTO and I-131, due to positive results of total body and urine monitoring of these radionuclides in the worker.

2 DESCRIPTION OF THE ACTIONS

During the early morning hours of 17 July 2019 a radiation protection officer of an argentine reactor decided to send a worker to perform a maintenance task with the suitable protective equipment for

aerosols. Although a gas and aerosol leak was not expected, high concentrations of them were recorded in other area that night, so the officer decides to send the worker with adequate protective equipment to prevent aerosol inhalation. It was considered that the inhalation of noble gases was not going to be significant, and if it was the case, the internal dose would be negligible based in the safety standards [2, 4].

At 12:30 a.m. the worker entered the controlled area. One hour later, performing a specific task that lasted 7 minutes, his EPD dosimeter alarm activated with a dosimeter peak reading of 5000 $\mu Sv.h^{-1}$ for beta irradiation. Simultaneously, a system (KLK 90) located one floor above measured a peak of 6 DAC of HTO in the environment during the time that the task last.

After decontamination, the worker was unable to exit through the portals; therefore, his total body measurement was programmed. Xe-133 and Xe-135 were detected in his thorax by measuring him with an Accuscan detector around 10 hours later. The internal dosimetry service of the facility established a special monitoring comprised of successive *in vivo* and *in vitro* measurements in the following days. The results of the measurements are presented in Table 1.

Table 1: Results of *in vivo* and *in vitro* measurements made to the worker

Date	Time	Measurement of total body retention of Xe-133 ± 1σ[(a)] (Bq)	Measurement of total body retention of Xe-135 ± 1σ[(a)] (Bq)	Measurement of urine excretion of I-131 ± 1σ[(a)] (Bq. l^{-1})	Measurement of urine excretion of HTO ± 1σ[(a)] (Bq. l^{-1})
July 17	09:11 a.m.			$6.0\times10^{1}\pm1.2\times10^{0}$	
	09:57 a.m.				$8.88\times10^{4}\pm1.8\times10^{3}$
	12:10 p.m.	$3.47\times10^{4}\pm 2.0\times10^{3}$	$2.05\times10^{3}\pm2.8\times10^{2}$		
July 18	10:31 a.m.	$3.68\times10^{3}\pm2.5\times10^{2}$	$3.2\times10^{1}\pm1.8\times10^{1}$		
	11:00 a.m.			$1\times10^{1}\pm0.2\times10^{0}$	
	02:13 p.m.	$1.91\times10^{3}\pm1.7\times10^{2}$	<LOD[(b)]		
	03:28 p.m.	$1.83\times10^{3}\pm1.6\times10^{2}$	<LOD		
	03:37 p.m.	$1.91\times10^{3}\pm1.6\times10^{2}$	<LOD		
	04:11 p.m.				$8.88\times10^{4}\pm1.8\times10^{3}$
July 19	12:55 p.m.	$5.33\times10^{2}\pm1.6\times10^{2}$	<LOD		
July 20	04:36 p.m.	<LOD[(b)]	<LOD		
July 24	11:57 a.m.	<LOD	<LOD	<LOD[(b)]	$5.85\times10^{4}\pm1.2\times10^{3}$

[(a)]Activity uncertainty quoted at 1 sigma

[(b)]LOD: Limit of Detection, for Xe-133= 40 Bq, for Xe-135=15 Bq, I-131=0.1 $Bq.l^{-1}$

At 9 a.m. of July 17 an open valve was discovered and gases concentrations were measured in the place where the worker was exposed. In Table 2 are presented the results of gases concentrations measured around 8 hours later the peak of the gases released was detected.

Due to the fact that the concentration of gases at the moment of the event was unknown and there were not biokinetic models for the radionuclides detected in the worker, neither in GSR part 3 nor in the ICRP reports [4, 5, 6] that explains the retention of Xenon in the thorax, the radiation protection area of the facility did not have enough information to assign an internal dose to the worker. For this reason, a formal request for assistance was sent to the Argentine Nuclear Regulatory Authority (ARN) on 19 July, where independent bioassays and dose assessments were asked. A venous blood sample from the worker was taken for biological dosimetry analysis in ARN Biodosimetry Laboratory, reporting on 26 July an average dose received in the whole body <0.1Gy

Table 2: Results of gases concentrations registered around 8 hours after the peak of the gases released was detected. Dose coefficients and the physical half-life of each radionuclide detected are also presented [4].

Radionuclide	Concentration [$Bq.m^{-3}$] eight hours after the event	Physical half life	$e(50)_{inh}$ [$Sv.Bq^{-1}$]	Effective dose rate per unit integrated air concentration [$Sv.d^{-1}$ per $Bq.m^{-3}$]
Xe-133	2.96×10^{8}	5.24 d	------	1.20×10^{-10}
Xe-135	1.23×10^{7}	9.1 h	------	9.60×10^{-10}
Xe-138	2.00×10^{7}	0.237 h	------	4.70×10^{-10}
Xe-135m	6.88×10^{5}	0.255 d	------	1.60×10^{-9}
Kr-87	5.37×10^{5}	1.27 h	------	3.40×10^{-9}
I-131	2.73×10^{5}	8.04 d	1.10×10^{-8}	------
I-133	2.90×10^{5}	20.8 h	2.10×10^{-9}	------
Co-60	9.88×10^{6}	5.27 y	1.70×10^{-8}	------

3 METHODOLOGY FOR INTERNAL DOSE ASSESSMENT

It was established that the worker's measurement data reported by the internal dosimetry laboratory detected in his thorax would correspond to retention data of the xenon mainly in fatty tissue, since no biokinetic model predicts that a person exposed to Xenon retains during several hours or days this gas in the lungs, but evidence that it is long retained in fatty tissue was found [6, 7, 8]. Additionally, it was observed that the measurements of internally deposited xenon were reasonably consistent with the behaviour of retained xenon in systemic tissues mainly in fat, observed in subjects and in model predictions found in literature [6, 7, 8]. Under these circumstances, it was considered that using the Xe-133 dose factors recommended by ICRP 128 for patients treated with this radionuclide by re-inhalation of the gas for 10 minutes [8] could be used for estimating Xe-133 internal dose in this scenario. Nevertheless, for applying that dose factor the intake was needed, in addition, no Xe-135 dose factor was available in that report.

While the direct dose assessment method arose as an alternative to assess the internal dose due Xe-133 and Xe-135 using the available measurement data, these measurements were not enough, since there were no data of initial lung deposition and systemic tissue uptake, which were decisive. Once again, the estimation of the intake of these radionuclides was critical, for which it was necessary to reconstruct the concentration of the gases released at the time of the event.

Consequently, ARN personnel of Radiological Protection and Physical Dosimetry areas reconstructed the exposure conditions through a concentration of 9.3×10^{8} $Bq.m^{-3}$ of Xe-133 and 7.3×10^{7} $Bq.m^{-3}$ of Xe-135. The values of the $H_p(10)$ and $H_p(0.07)$ of the EPD personal dosimeter of the worker were also used taking as reference the skin dose coefficients by immersion in the cloud from the Federal Guidance Report No.12 [9]. Knowing these concentrations, it was possible to estimate the intakes of 130.2 MBq of Xe-133 and 10.22 MBq of Xe-135, assuming a standard worker's respiration rate of 0.02 $m^3.min^{-1}$ and an exposure time of 7 minutes.

Next, two methods were proposed to assess xenon radioisotopes effective dose. The first one, applying the Xe-133 dose coefficient recommended by ICRP 128 for patients treated with this radionuclide by re-inhalation of the gas for 10 minutes [8]. The second one, implementing the direct dose assessment method. Direct dose assessment method requires calculating the area under the retention activity data, in order to determine the number of nuclear transformations in a specific organ or tissue identified as source. The committed equivalent dose deposited in the target organ is calculated as the product of the

number of nuclear transformations and the dose factor in the target organ per disintegration in the source [10]. Following the biokinetic models found in literature, two main source organs were identified: lungs and fatty tissues; therefore, with the purpose of a proxy absorbed dose estimation, it was assumed that xenon not present in the lungs was distributed uniformly throughout the rest of the body. The number of nuclear transformations of rest of the body compartment was estimated using the trapezoidal method and taken into account the measured worker data. For lungs, the value of the cumulated activity for this organ recommended in ICRP 128 for the patient was assumed [8].

The direct dose assessment was implemented through the OLINDA code version 1.1 [11], which has in its database the dose factors per disintegration for various types of anthropomorphic phantoms (based on the Oak Ridge models) and radionuclides, including Xe-133 and Xe-135. In order to calculate the dose, this program requires the selection of the human model, the radionuclide of interest, and to enter the values of the time-integrated activity of the different source organs. In this way it was possible to have a proxy estimation of the doses in the different organs for both isotopes, Xe-133 and Xe-135, using an adult male phantom.

The positive results of HTO and I-131 in urine bioassays were evaluated using the biokinetic models recommended for the worker [12], under the assumption of acute inhalation and no contribution from previous intakes of these radionuclides, using the IMBA code [13].

4 RESULTS

Table 3 presents an estimation of the effective dose and the absorbed dose in different tissues. It was assumed a Xe-133 intake of 130.2 MBq (based on the modeled concentration of Xe-133 in air) and using the Xe-133 retention model recommended for patients treated with this radionuclide by rebreathing the gas for 10 minutes, and considering the dose factors recommended by ICRP 128 for this scenario [8]. $\times 10^{-1}$

Table 3: Committed absorbed dose in different tissues and committed effective dose by inhalation of 130.2 MBq of Xe-133 using the biokinetic model of the patient recommended in ICRP 128 [8].

Tissues	Committed absorbed dose (mGy)	Tissues	Committed absorbed dose (mGy)
Adrenals	1.4×10^{-1}	Muscles	1.4×10^{-1}
Bone surfaces	1.8×10^{-1}	Oesophagus	1.4×10^{-1}
Brain	1.4×10^{-1}	Ovaries	1.6×10^{-1}
Breast	1.4×10^{-1}	Pancreas	1.6×10^{-1}
Gallbladder wall	1.6×10^{-1}	Red marrow	1.4×10^{-1}
Stomach wall	1.4×10^{-1}	Skin	1.3×10^{-1}
Small intestine	1.6×10^{-1}	Spleen	1.4×10^{-1}
Colon wall	1.4×10^{-1}	Testes	1.4×10^{-1}
(Upper Large Intestine wall)	1.4×10^{-1}	Thymus	1.4×10^{-1}
(Lower Large Intestine wall)	1.6×10^{-1}	Thyroid	1.4×10^{-1}
Heart wall	1.4×10^{-1}	Urinary Bladder wall	1.4×10^{-1}
Kidneys	1.4×10^{-1}	Uterus	1.6×10^{-1}
Liver	1.4×10^{-1}	Remaining organs	1.4×10^{-1}
Lungs	1.6×10^{-1}	**Effective dose (mSv)**	$\mathbf{1.4\times10^{-1}}$

Tables 4 and 5 present the results of the committed equivalent doses in different tissues and the effective doses for Xe-133 and Xe-135 respectively, implementing the direct dose assessment, using the *in vivo* measurement data of the worker.

Table 4: Committed equivalent doses in different tissues and committed effective dose due to the intake of Xe-133 implementing the direct dose assessment, using the *in vivo* measurement data of the worker.

Tissues	Committed Equivalent Dose (mSv)	Tissues	Committed Equivalent Dose (mSv)
Adrenals	2.08×10^{-1}	Muscle	1.99×10^{-1}
Brain	2.02×10^{-1}	Ovaries	2.12×10^{-1}
Breasts	1.91×10^{-1}	Pancreas	2.12×10^{-1}
Gallbladder Wall	2.11×10^{-1}	Red Marrow	1.63×10^{-1}
LLI Wall	2.11×10^{-1}	Skin	1.87×10^{-1}
Small Intestine	2.11×10^{-1}	Spleen	2.07×10^{-1}
Stomach Wall	2.07×10^{-1}	Testes	1.98×10^{-1}
ULI Wall	2.10×10^{-1}	Thymus	2.03×10^{-1}
Heart Wall	2.07×10^{-1}	Thyroid	2.06×10^{-1}
Kidneys	2.04×10^{-1}	Urinary Bladder Wall	2.08×10^{-1}
Liver	2.07×10^{-1}	Uterus	2.12×10^{-1}
Lungs	1.68×10^{-1}	**Effective dose (mSv)**	**1.95×10^{-1}**

Table 5: Committed equivalent doses in different tissues and committed effective dose due to the intake of Xe-135 implementing the direct dose assessment, using the *in vivo* measurement data of the worker.

Tissues	Committed Equivalent Dose (mSv)	Tissues	Committed Equivalent Dose (mSv)
Adrenals	3.94×10^{-2}	Muscle	3.67×10^{-2}
Brain	3.57×10^{-2}	Ovaries	4.05×10^{-2}
Breasts	3.44×10^{-2}	Pancreas	4.03×10^{-2}
Gallbladder Wall	4.02×10^{-2}	Red Marrow	2.96×10^{-2}
LLI Wall	3.99×10^{-2}	Skin	3.37×10^{-2}
Small Intestine	4.02×10^{-2}	Spleen	3.85×10^{-2}
Stomach Wall	3.88×10^{-2}	Testes	3.67×10^{-2}
ULI Wall	3.99×10^{-2}	Thymus	3.76×10^{-2}
Heart Wall	3.88×10^{-2}	Thyroid	3.77×10^{-2}
Kidneys	3.85×10^{-2}	Urinary Bladder Wall	3.96×10^{-2}
Liver	3.85×10^{-2}	Uterus	4.07×10^{-2}
Lungs	3.24×10^{-2}	**Effective dose (mSv)**	**3.55×10^{-2}**

The effective doses by internal exposure to HTO and I-131 were estimated using the urinary excretion data showed in Table 1 fitted to their corresponding intake retention fractions and the dose coefficients for workers. The estimated committed effective doses by exposure to HTO and I-131 are equal to

7.57×10^{-2} mSv and 1.52×10^{-3} mSv respectively, under the assumption that an acute inhalation occurred and that there is no contribution from previous intakes of these radionuclides.

Table 6 presents the contribution of each radionuclide to the committed effective dose and the total committed effective dose for the two methods implemented to estimate the dose due to the intake of xenon isotopes.

Table 6: Contribution of each radionuclide to the committed effective dose and the total committed effective dose for the two implemented methods.

Radionuclide	Contribution to Committed Effective Dose (mSv) Method 1	Contribution to Committed Effective Dose (mSv) Method 2
Xe-133	1.43×10^{-1}	1.95×10^{-1}
Xe-135		3.55×10^{-2}
H-3	7.57×10^{-2}	7.57×10^{-2}
I-131	1.52×10^{-3}	1.52×10^{-3}
Total Committed Effective Dose (mSv)	2.20×10^{-1}	3.01×10^{-1}

5 CONCLUSIONS

In this work, the chronological actions to reconstruct the worker´s intake and to estimate the committed effective dose, due to unexpected exposure to high concentration of gases during a maintenance task were presented. The description of the methodologies implemented to estimate the contribution to the total effective dose from the internal exposure to Xe-133, Xe-135, HTO and I-131 were also included. The assessment of internal dose by xenon isotopes was performed without biokinetic models or dose coefficients of reference for occupational intake of these isotopes.

The committed effective doses for internal exposure to Xe-133 was estimated following two methods: the first one using the dose factors recommended by ICRP for patients treated with Xe-133 (for 10 min), and the second one using the MIRD methodology and data from *in vivo* worker's Xe-133 measurement reported by the internal dosimetry laboratory. The estimated effective dose for exposure to Xe-133 using method 2 was very similar to that estimated using method 1, therefore it could be concluded that the results of positive chest measurements, reported by the internal dosimetry laboratory, were consistent with retention of xenon in fatty tissue.

Since the contribution to the dose from exposure to Xe-135 cannot be obtained by applying method 1, it was recommended that the total committed effective dose value assigned to this event, taking into account all the measured radionuclides, be considered 0.3 mSv.

Finally, although the dose estimated was much lower than the dose limits and dose restrictions for workers, the causes that gave rise to the event are being analyzed.

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