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JRC TECHNICAL REPORT

The renewed whole body counter of the European Commission at the JRC Ispra site

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Foreword

The Whole Body Counter (WBC) at the Joint Research Centre (JRC) Ispra has been recently upgraded. This technical report describes the functionalities of the renewed WBC laboratory.

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Abstract

The Whole Body Counter (WBC) at the Joint Research Centre (JRC) Ispra is an upgraded monitoring device available for European research in internal dosimetry. A VETO anti-muonic system has been installed on the ceiling of the WBC and connected in anti-coincidence to four new detectors by interfacing with an Integrated Digital Acquisition System (IDAS), permitting a reduction in the background level of more than 30%. Using the new HpGe detector it's possible to obtain MDA=24 Bq of ^{137}Cs in a 20 min measurement, similar to Minimum Detectable Activity (MDA) using 203 mm (diam) x 102 mm NaI(Tl) (25 Bq), with better resolution.

1 Introduction

By means of inhalation, ingestion and skin absorption, everyone is a mobile environmental sampler and everyone, with his personal metabolic system, is a living biological sample at the same time. The Whole Body Counter Laboratories allow measuring the radioactive elements collected by our biological-sampling system in a particular place at a certain time and it is used for the routine checking of internal contamination of nuclear workers (1), (2), (3), (4). Since February 1966 at the JRC Ispra a whole-body counter has been operational with one NaI(Tl) detector (203 mm diam x102 mm) for incorporating monitoring of gamma-emitting radionuclides by workers of the on-site nuclear facilities and in case of nuclear emergency, in conformity to European Radiation Protection Directives and Italian legislation. After 53 years the detection and the electronic acquisition system have been renewed maintaining the same structure of the laboratory, with a reduction of more than 30% of natural radiation background and consistent improvement of energy-detection range, energy-resolution and MDA levels.

2 Monitoring Room

The WBC is located in a building at 230 meters above sea level and the access to the measuring room is via an open shielded labyrinth. The measuring room is internally 170 cm x 220 cm large x 206 cm height and is climatised by filtered external air. The mean dose rate inside the monitoring room is 19(6) nSv/h (measured by inorganic scintillator, Automess 6150 ADb monitor) and the mean ^{222}Rn concentration is 20(8) Bq/m^3 (measured by ionisation chamber, Genitron Alpha-Guard monitor). There are two kinds of radiation shielding: passive and active. The passive shield consists of 1 mm Cu, 2 mm Cd, and 10 cm selected low-level background of Pb. Moreover, under the floor of the laboratory for 4 meters depth there are pieces of Carrara marble at very low-level background to shield further the terrestrial radiation. Together with new detectors, an active shield (VETO) of 11 organic plastic scintillators (Nuvia/Else Nuclear), 240 cm x 270 cm, in anti-coincidence to each detector in the monitoring room was installed on the roof of the measuring room, to reduce the cosmic radiation background contribution (5). (Figure 1)

Fig.1: Overview of the Whole Body Counter Laboratory with VETO detectors

3 Detectors and Electronics

4 detectors are installed in the monitoring room (WBC detectors):1 NaI(Tl) and 3 HpGe used for 3 internal measurement methods (whole body, lungs, thyroid). Table 1.

Table 1. Detectors

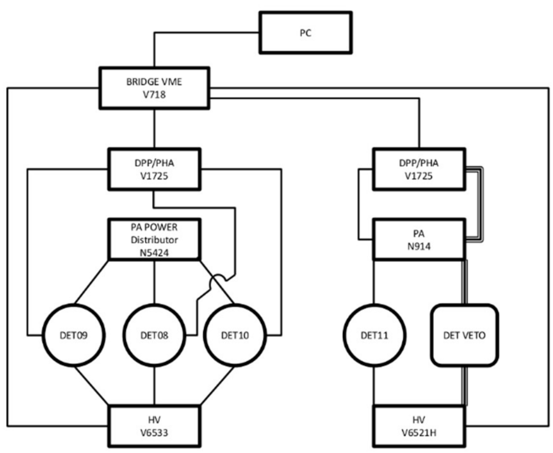
DETECTOR	TYPE	MANUFACTURED	DIAMETER [mm]	LENGTH [mm]	MASS [kg]	WINDOW MATERIAL	WINDOW THICKNESS [mm]	FWHM	RELATIVE EFFICIENCY
DET08	HpGe,p-GEM-SP	EG&G Ortec	85.0	31.6	0.954	Carbon-epoxy	0.76	1.87 keV [1]	53%
DET09	HpGe,p-GEM-SP	EG&G Ortec	84.7	32.1	0.962	Carbon-epoxy	0.9	1.67 keV [1]	56%
DET10	HpGe, p-Xt-R	Canberra-Mirion	83.3	69.0	1.986	Carbon-epoxy	0.6	1.79 keV [1]	124%
DET11	NaI(Tl)	Scionix	203	102	12.11	Al	0.5	46 keV [1] - 7.0% [2]	990%

[1] FWHM at 1332 keV (60Co)

[2] FWHM at 661 keV (137Cs)

DET 11 is a NaI(Tl) scintillator detector, manufactured by Scionix, in 2019. A light guide of undoped NaI (diam 203 mm x 51 mm) shields the gamma radiation emitted by natural radionuclides of the 3 PMTs components. Three K-free glass PMTs (ET 9265) have been selected to reduce the background gamma radiation rate from ^{40}K. To reduce the electronic noise the 3 PMTs are connected to a coincidence digital system; the low energy spurious background signals due to the single PMT are then eliminated. DET 08 and DET 09 are coaxial HpGe, GEM-SP model detectors, manufactured by EG&G Ortec, in 2018. The DET10 is a coaxial HpGe, Xt-R model, manufactured by Canberra-Mirion, in 2018. A VETO system of 11 organic plastic scintillators, manufactured by Nuvia-Else Nuclear, in 2018, has been installed on the ceiling of the WBC. The plastic scintillator is polystyrene (density = 1.03 g/cm^3). The maximal emission sensitivity is 440 nm, compatible to the spectral response of the ET Enterprises 9266B photo-multiplier tubes. The old NIM analog electronics has been substituted by an Integrated Digital Analysis System (IDAS) with HV supplies (CAEN/V6533-V6521H), 2 Pre-amplifier units (CAEN/N914), 2 Digital Pulse Processing Units (CAEN/V1725) and 1 VEM/USB2.0 interface (CAEN/V1718). Each detector is connected to a charge sensitive pre-amplifier: the 3 HpGe's (DET08, DET09 and DET10) to internal Ortec and Canberra PAs (Low Voltage Power Supply CAEN N5424), 11 PMTs of VETO and 3 PMTs of NaI(Tl) (DET11) to external CAEN/N914 PAs. DET08, DET09, DET10 and DET11 are connected to a digitalizing acquisitions system (CAEN) in anti-coincidence to the VETO anti-muon radiation detection system (Figure 2).

Fig.2: Measuring system



All analog output signals of DET08, DET09,DET10, DET11 and VETO are processed by 2 DPP (Digital Pulse Processing) Units CAEN/V1725 (Digital Constant Fraction Discriminators, Coincidence between 3 PMT of DET11, anti-coincidence between VETO and WBC detectors, Trapezoidal filters for Pulse Height Analysis). The module CAEN V1718 allows the control of the 2 DPP and all the High Voltage Power Supply modules (CAEN V6533P/V6521H) with one unique link to the external computer. By the connection to an external PC with the acquisition software CAEN Compass, it is possible to visualize the signal digitized by each acquisition channel, to set the acquisition parameters triggering coincidence/anti-coincidence signals between channels and control the digital filter PHA (Pulse Height Analysis). IDAS is interfaced to another computer with Canberra Genie 2k software (standard equipment up till now used at WBC laboratory) for the elaboration of gamma spectra by MCA 8192 channels. The VETO system allowed to reduce of about 30% the background level in the range 40 and 2700 keV for all the detectors in the monitoring room (Table 2, Table 3, Figure 3, Figure 4).

Table 2. Background

		VETO OFF		VETO ON	
DETECTOR	Measurement Time (s)	(s^{-1})	(s^{-1} kg^{-1})	(s^{-1})	(s^{-1} kg^{-1})
DET08 [1]	50000	2.38(1)	2.50(1)	1.79(1)	1.87(1)
DET09 [1]	50000	2.44(1)	2.54(1)	1.79(1)	1.86(1)
DET10 [1]	191000	3.49(1)	1.76(1)	2.48(1)	1.24(1)
DET11 [2]	50000	10.91(2)	0.90(2)	7.80(1)	0.64(1)

[1] 40 - 2700 keV

[2] 40 - 2300 keV

Table 3. Background Peaks

E_γ (keV)	RADIONUCLIDE	DET08 (h^{-1} kg^{-1})	DET09 (h^{-1} kg^{-1})	DET10 (h^{-1} kg^{-1})
46	^{210}Pb	19(3)	31(4)	3(1)
63	^{234}Th	23(4)	41(4)	< 1.2
93	^{234}Th	72(4)	79(4)	4(1)
186	^{226}Ra/^{235}U	50(4)	51(4)	5(1)
238	^{212}Pb	52(3)	44(3)	28(1)
242	^{214}Pb	6(1)	5(1)	5(1)
295	^{214}Pb	15(2)	12(2)	13(1)
351	^{214}Pb	27(2)	21(2)	24(1)
511	Annihilation	48(3)	58(3)	54(1)
583	^{208}Tl	20(2)	17(2)	14(1)
609	^{214}Bi	22(1)	19(1)	25(1)
661	^{137}Cs	3(1)	2(1)	2(1)
911	^{228}Ac	8(1)	8(1)	9(1)
1120	^{214}Bi	4(1)	4(1)	6(1)
1173	^{60}Co	<1.5	<1.4	< 0.5
1332	^{60}Co	<2.0	<1.4	< 0.4
1460	^{40}K	9(1)	9(1)	9(1)
1764	^{214}Bi	3(1)	4(1)	6(1)
2614	^{208}Tl	9(1)	7(1)	10(1)
	Measurement Time (s)	50000	50000	191000

Fig.3: Background spectra of DET 10 (HpGe) with and without VETO

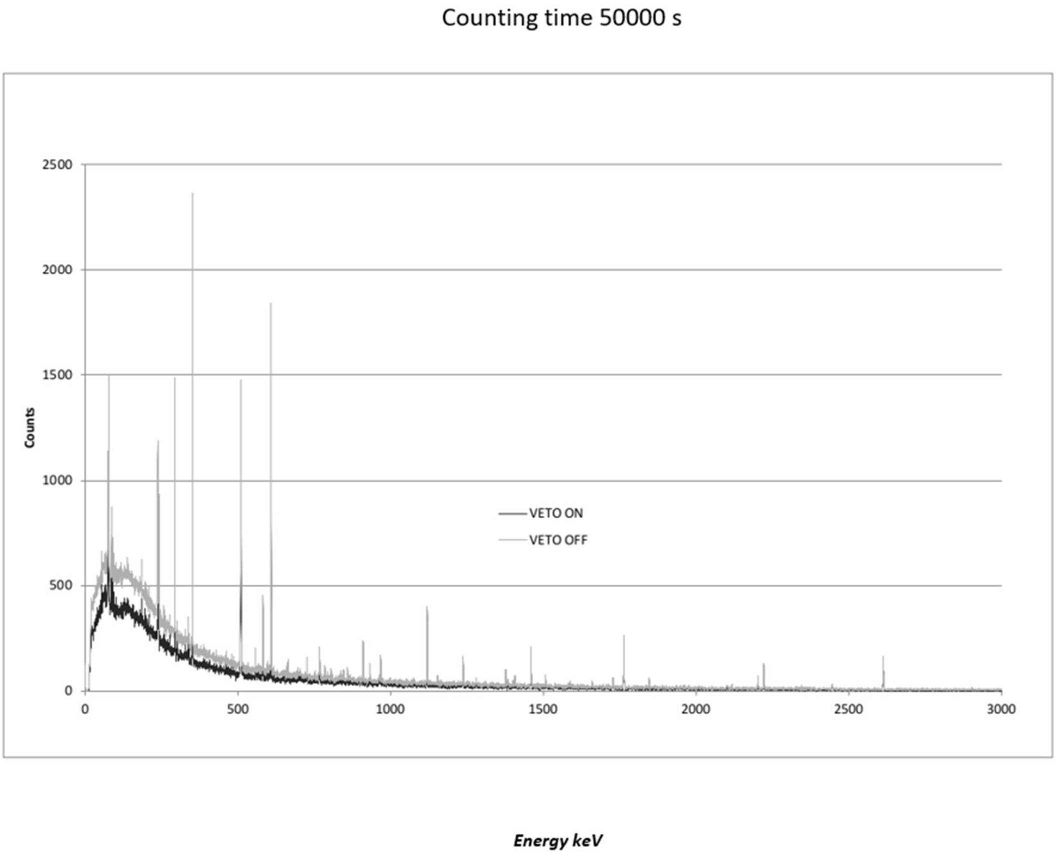
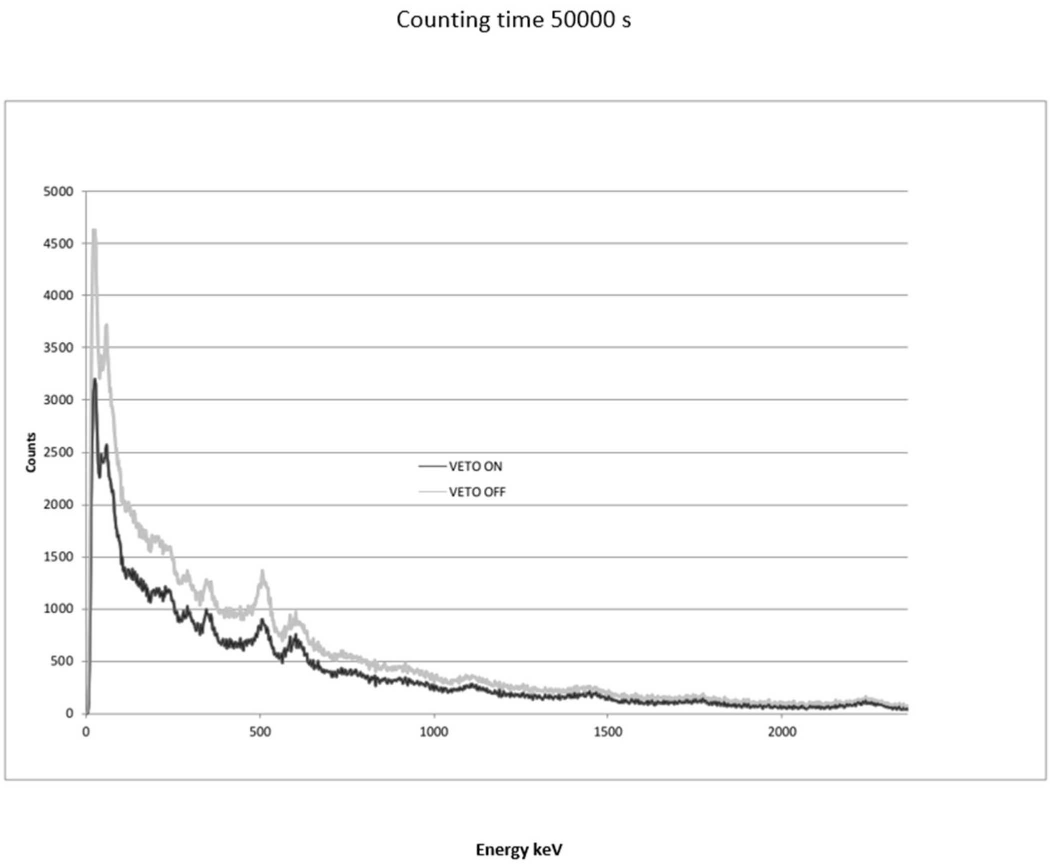


Fig.4: Background spectra of DET 11 (NaI-Tl) with and without VETO



4 Measurement Methods

The WBC laboratory has set-up three internal measurement methods (typical measuring time 20 min):

a) Whole body;

b) Lungs;

c) Thyroid.

The activity is calculated as:

$$A = \frac{n_{N,E}/t_g}{P_E \cdot \varepsilon_E \cdot f_E} \qquad (1)$$

Where A is expressed in Becquerel, $n_{N,E}$ is the peak net counts; t_g is the measuring time (s); P_E is the branching ratio; ε_E is the detection efficiency for the gamma energy E and f_E is the measuring correction factor. In particular f_E in defined as:

$$f_E = f_{sw} \cdot f_{pos} \qquad (2)$$

Where f_{sw} is the software factor and f_{pos} is the position factor (it was assumed $f_{sw} = f_{pos} = 1$). The MDA for each method and for a particular radionuclide, considering the specific gamma branching ratio, is calculated at significance level α = 0,05 and statistical power (1- β) =0,95 conforming to references (6),(7).The formula used is:

$$MDA = \frac{k\frac{1}{t_g\, \varepsilon_E\, P_E}\left\{k+2\sqrt{\left[\frac{P}{2n_m}n_0+\left(\frac{P}{2n_m}\right)^2 n_0\right]}\right\}}{1-k^2\left[\frac{u^2(\varepsilon_E)}{\varepsilon_E{}^2}+\frac{u^2(P_E)}{P_E{}^2}\right]} \qquad (3)$$

in which k is the quantile of the standardized normal distribution for the probability (1- α) =(1- β) =0,95; t_g is the measuring time (s), ε_E is the detection efficiency for the gamma energy E, P_E is the branching ratio at energy E, P is the number of channels within the peak region, n_0 is the number of counts in the right and left region of the peak of interest and n_m is the number of channels in the right or left region of the peak of interest. The relative standard combined uncertainty is calculated as (8):

$$u_{rel}(A) = \sqrt{u_{rel}^2(n_{N,E}) + u_{rel}^2(t_g) + u_{rel}^2(P_E) + u_{rel}^2(\varepsilon_E) + u_{rel}^2(f_{sw}) + u_{rel}^2(f_{pos})} \qquad (4)$$

Where $u_{rel}(n_{N,E})$ is the relative standard uncertainty for the peak net counts, $u_{rel}(t_g)$is the relative standard uncertainty for the measuring time, $u_{rel}(P_E)$ is the relative standard uncertainty for the branching emission ratio, $u_{rel}(\varepsilon_E)$ is the relative standard uncertainty for the efficiency, $u_{rel}(f_{SW})$ is the relative standard uncertainty for the software factor and $u_{rel}(f_{pos})$ is the relative standard uncertainty for the position.

Table 4 shows the typical uncertainty budget for method 1 (DET 10).

Table 5 shows typical expanded uncertainty values for each method for 100 Bq of specific radionuclides.

Table 6 shows sensitivity and MDA values for each method for specific radionuclides.

Table 4 - Typical uncertainty budget for a whole body contamination with 100 Bq of ^{137}Cs (DET10)

Parameter	Uncertainty Type	Relative standard uncertainty [%]	
Measuring time t_g [s]	A	$u_{rel}(t_g)$	<0,01
Peak net counts $n_{N,E}$	A	$u_{rel}(n_{N,E})$	14,4
Detection Efficiency ε_E	A	$u_{rel}(\varepsilon_E)$	4,2
Branching ratio P_E	B	$u_{rel}(p_E)$	0,2
Software factor f_{SW}	B	$u_{rel}(SW)$	4,0
Position factor f_{pos}	A	$u_{rel}(pos)$	4,0

Relative combined standard uncertainty [%]	$u_{rel}(A)$	16,0
Expanded Uncertainty [Bq] (k=2)	U(A)	32,0

Table 5 - Typical Expanded Uncertainty (k=2) for a measurement of 100 Bq

Method	Radionuclide	Activity (Bq)	U (Bq)
Whole Body DET10	^{137}Cs	100	32
Whole Body DET11	^{137}Cs	100	28
Lungs	^{241}Am	100	17
Thyroid	^{131}I	100	20

Table 6. Sensitivity and MDA

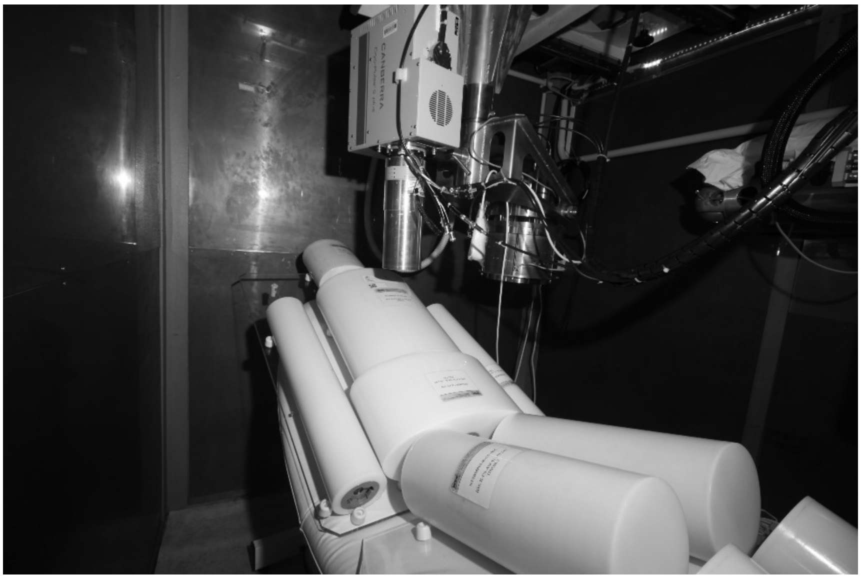
DETECTOR	METHOD	RADIONUCLIDE	ENERGY (keV)	Sensitivity (s^{-1} Bq^{-1})	MDA (Bq) (t=1200 s)
DET08 + DET09	LUNGS	^{241}Am	54.54	1.85E-03	11
DET09	THYROID	^{131}I	364.49	7.12E-03	4
DET10	WHOLE BODY	^{137}Cs	661.65	5.07E-04	24
DET11	WHOLE BODY	^{137}Cs	661.65	5.43E-03	25
DET01*	WHOLE BODY	^{137}Cs	661.65	3.20E-04	35

* Old detector (without VETO system), not in use anymore

4.1 Internal Method 1: WHOLE BODY

DET10 (HpGe) is normally used for routine measurements of internal contamination of whole body. DET 11 NaI(Tl) may be used in alternative for rapid emergency measurements (high efficiency/low resolution) of whole body and in case of maintenance of the HpGe detectors. Both of the detectors are mounted on a truck moving on two tracks fixed on the ceiling. The distance between the detector and the subject is adjustable by a motorized dentist's chair. More specifically, the HpGe detector (DET10) is placed above the subject at 7.5 cm distance from the surface of the chest, while the NaI(Tl) detector (DET11), placed also above the subject, is a 5.0 distance from the surface of the chest. The detectors has been calibrated using a Bottle Manikin Absorber (BOMAB) reference phantom (Nuclear Technology Services, Inc.) with ^{241}Am (32.8 kBq), ^{137}Cs (9.5 kBq) and ^{40}K (11.0 kBq) uniformly distributed reference sources (9). (Figure 5). The efficiency curves have been validated by measurements with another BOMAB with ^{152}Eu uniformly distributed reference source (A= 21.6 kBq).

Fig.5: Monitoring room with reference BOMAB and DET 10 for Whole Body analysis



4.2 Internal Method 2: LUNGS

DET08 and DET 09 (HpGe) are normally used for measurements of contamination in lungs. Both of the detectors are mounted on a mechanical support fixed on the floor of the measuring room. The distance between the detectors and the subject to be measured is adjustable by a motorized dentist's chair. More specifically, the two detectors are placed above the subject at 3.0 cm distance from the surface of the chest. Each detector produces one independent spectrum and the comparison of them allows to detect an inhomogeneous distribution of the contamination of the lungs. The detector has been calibrated (HpGe) using an LLNL (Lawrence Livermore National Laboratory) phantom with 3 sets of synthetic lungs uniformly contaminated with reference sources of ^{241}Am (33.6 kBq), ^{137}Cs (19.4 kBq) and ^{226}Ra (223.1 kBq) (Radiology Support Devices, Inc.).

4.3 Internal Method 3: THYROID

DET 09 is normally used also for measurements of contamination in thyroid. The support and the positioning system is the same of this for internal method 2. More specifically, the detector is placed above the subject at 7.0 cm distance from the surface of base of the neck. The detector has been calibrated using an LLNL phantom with a synthetic thyroid uniformly contaminated with reference sources of ^{129}I and ^{226}Ra and by point standard sources of ^{57}Co, ^{133}Ba, ^{137}Cs, ^{241}Am (Eckert & Ziegler).

5 Conclusions

The low-level background and the high efficiency HpGe installed detectors, together with the anti-muon shield and the Integrated Digital Analysis System gives the JRC-WBC Ispra the possibility to measure internal body contamination of gamma-emitter radionuclides at low-level MDA and high resolution, in conformity to European Directive 2013/59/EURATOM (10).

Therefore the renewed Whole Body Counter at the JRC Ispra can continue to be considered a centre of excellence of European Research and Service in the Radiation Protection field, open to scientific co-operation with national and international Laboratories, Universities and Institutions.

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