Nordic Intercomparison Campaign for Whole Body Counters – Evaluation of the Performance of the Facilities and Inventory of Regional Resources

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Abstract
Results of the regional intercomparison campaign conducted in 2010 and 2011 are presented and discussed. This activity was promoted in the framework of the Nordic Nuclear Safety Research (NKS) collaboration for regional cooperation in nuclear safety, radiation protection and emergency preparedness. The goals were to evaluate the quality status of whole body counting measurements by means of a proficiency test exercise, setting up an on-line library for the management of the use of calibration phantoms in the region and an to make inventory of the regional resources. The St. Petersburg whole body phantom was circulated in the region for the measurements together with two sets of fully traceable radioactive material (Cs^{137} and K^{40}). As part of this activity a web based library for regional phantoms was set up as the tool for managing the loan of the regional phantoms. The regional inventory of resources for *in-vivo* measurements revealed that the whole body counting assets have been maintained compared to 2004. Both the field laboratories and the stationary ones are equipped with sophisticated whole-body counting systems with Ge- and/or NaI-detectors. The regional competence is good and retains experienced staff but a new generation is coming that needs training and exchange of experiences, which emphazises the importance of keeping the practice of intercomparison exercises.

Keywords
Whole body counting, intercomparison, phantom library

1. Introduction

Whole body counting remains one of the most important tools for internal dosimetry, offering the possibility to quantify the internally deposited radionuclides directly in a speedy way and to detect insoluble materials with long retention times. A whole body counting system can detect levels of most gamma emitters (>200 keV) at levels far below that which would cause adverse health effects in man. A typical detection limit for radioactive caesium is around 40 Bq. The Annual Limit on Intake (based on the worker dose limit that is 20 mSv) is about 2 MBq for caesium-137. The amount of naturally occurring radioactive potassium, present in humans, is also easily detectable.

This paper presents the results of the regional campaign for gathering information on the regional resources for in-vivo measurement of internal radioactivity and evaluating the status of measurement quality. This activity was promoted in the framework of the Nordic Nuclear Safety Research (NKS) collaboration for regional cooperation in nuclear safety, radiation protection and emergency preparedness.

The compilation of information on the regional resources was performed by distributing of a questionnaire based on information collected in in 1994 and 2004 (Rahola T. et al., 1994; Rahola T. and Falk R., 2006). The campaign in 2010 included implementing a web-based tool for the management of the loans of calibration phantoms in the region. The loan system was given the name “The Phantom library” and is also described here.

The quality of regional measurement was evaluated by means of an intercomparison exercise. The participating laboratories determined the activity of a phantom filled with two sets of certified radioactive materials in radioactive rods, uniformly spaced inside of the phantom. One set was caesium-137 and the other potassium-40. The St. Petersburg whole body phantom (also known as IRINA), jointly owned by the Nordic countries, was circulated. Nineteen facilities and arrangements for whole body counting, both stationary and field-based, participated in the exercise. The circulation of the phantom started in 2010 and five days were allowed for performing the measurements followed by five days for the transport to the next laboratory.

2. The regional resources

Table 1 summarizes the regional resources. The measurement methods are based on the acquisition of one or several spectral data, depending on the number of available detectors. The ORTEC family of software tools Maestro and Gammavision are the most used for data acquisition. In some cases Gammavision is also used for the spectral analysis. Most of the participants at stationary laboratories correct for the background by counting a blank phantom of the approximately same size as the calibration phantom. In many cases the calibration phantom IRINA is used without the activity rods, thus a blank background is acquired when a calibration is performed.

Table 1. Summary of the regional resources.

Name of facility	Type of laboratory	Meas. geometry	Detectors	Routine meas. time	Background meas. method & time	Routine radio-nuclides	Analysis software
Forsmark	Low background	Stationary Sitting	1 HpGe 53%	10 min	Empty and blank 14 h		Genie ESP
Westinghouse	Low background	Stationary lung counter Bed, static detectors	3 HpGe 50%	40 min	Blank 3 days	^{235}U	In-house method
Ringhals	Low background	Stationary Sitting	1 NaI 3x3” (thy) 1 HpGe 66%	8 min	Empty 100000 s	^{131}I ^{58}Co, ^{60}Co, ^{95}Nb, ^{95}Zr, ^{137}Cs	Gammavision
Oskarshamn	Low background Collimated detectors	Stationary Dedicated chair WBC-6000	1 NaI 1x 1.5” (thy) 2HpGe 30%	10 min 10 min	Empty 63 h	^{131}I, ^{133}Ba ^{40}K, ^{54}Mn, ^{58}Co, ^{59}Fe, ^{65}Zn, ^{95}Nb, ^{95}Zr, ^{137}Cs	Genie 2000
Studsvik	Low background	Stationary Sitting	1 Coaxial Ge 50 %	10 min	Empty 14 h	^{137}Cs, ^{40}K, ^{60}Co	Genie 2000
Barsebäck	Low background	Stationary Sitting	1 HpGe 55 %	10 min	Empty 10 h	^{137}Cs, ^{40}K, ^{60}Co, ^{54}Mn, ^{125}Sb	Gammavision
IFE Halden	Low background	Stationary Sitting	1 NaI 3x3”	10 min	Empty 10 min	^{137}Cs, ^{60}Co	Genie 2000
IFE Kjeller	Low background	Stationary Sitting	1 NaI 6x4”	20 min	Empty 20 min	^{137}Cs, ^{60}Co, ^{223}Ra	Scintivision

Norge NRPA	Collimated detectors	Field-lab Sitting	1 HpGe 50%	10 min	Empty 1 h	^{137}Cs	Maestro and in-house excel sheet
NM/PET Rigshospitalet	Low background	Bed, static detector	4 Plastic scintillators 4 NaI 6x4”	600 s 1800 s	Empty and blank (600, 1800 s, respectively)	^{40}K, ^{47}Ca, ^{65}Zn, ^{111}In, ^{59}F, ^{83,84}Rb ^{99m}Tc	ABACOS Genie 2000
Iceland	Un-collimated detector	Field lab Palmer geometry	1 NaI 2.5x2.5”	20 min	Empty	^{137}Cs	Gammavision and in house program
University of Helsinki	Low background	Stationary Sitting	1 NaI 100x200 cm	1000 sec	Empty and blank 40 h	^{40}K, ^{137}Cs, ^{11}C, ^{18}F	Genie 2000 and in-house excel sheet
Finland STUK	Low background	Stationary Scanning bed static detectors	3 HpGe 25-50%	1000 sec	Blank 12 h	^{137}Cs, ^{40}K, ^{60}Co, ^{110m}Ag, ^{124}Sb	Maestro and in-house spectrum analysis
	Low background	Mobile unit; sitting geometry	2 HpGe 85%	1000 sec	Blank 12 h	^{137}Cs, ^{40}K, ^{60}Co, ^{110m}Ag, ^{124}Sb	Maestro and in-house spectrum analysis
FOI Umeå	Collimated detectors	Field-lab Mix geom. chair/arc	1 NaI 2x2” (thy) 1HpGe 50%	1000 sec 1000sec	Empty and blank 15 h	^{131}I, ^{133}Ba ^{137}Cs, ^{40}K, ^{60}Co, ^{152}Eu	Gammavision
Lund University at Malmö UH	Low background	Stationary Bed, static detectors	3 NaI plastic	1000 sec	Empty and blank	^{137}Cs, ^{40}K	Maestro and in-house method
Radiofysik Linköping	Collimated detectors	Stationary Scanning/ static bed with scanning detectors	2 NaI	30 – 60 min	Empty	^{99m}Tc, ^{123}I, ^{18}F	In house
Stockholm University	Low background Collimated detectors	Stationary Scanning bed with static detectors	6 NaI	20 min	Blank 1 h	^{40}K	In-house
University of Gothenburg	Low background	Stationary Scanning/ static detector static bed	2 NaI 5x4” 1 NaI 5x1/4” 4 NaI plastic 91x76x24 cm^3	varying	Empty	^{40}K, ^{99m}Tc, ^{211}At, ^{137}Cs, ^{60}Co	Accuspec and in-house manual calculation
Sweden SSM	Low background	Stationary Sitting in reclined position	1NaI (thy) 3 NaI 5x4” 1 HpGe for use in emergency situations	30 min 30 min 30 min	Empty Blank Irina neck 30 min Empty Blank IRINA 30 min Blank Livermore 30 min	^{131}I, ^{133}Ba ^{137}Cs, ^{40}K, ^{60}Co Nuclide ID purposes based on ^{152}Eu cal.	In-house MAESTRO-based code Genie 2000

3. The Nordic phantom library website

A phantom library website has been set up (www.nks.org/en/phantom_library.) Its purpose is to establish a loan system for the region’s calibration phantoms. The participants agreed that the phantom library website would definitely be positive for the regional network of whole body counting facilities. The jointly owned phantoms and two others from STUK were listed to be included in the website's list of phantoms. The list includes a total of 5 phantoms for total body calibration and thyroid calibration. The phantoms are listed with their contact person, permanent address and technical documentation.

The phantom library works the same as any other online library; the users must first register in order to check out the library's resources. Online requests for a loan generate two automatic electronic letters: one to the owner of the phantom and the other to the requester as a confirmation. An email address, phantomlib@nks.org, has been set up in order to serve as a node for the automatic messages generated by use of the library (Hansen H., 2010). The status of the library resources is updated after the completion of every loan request. In this way any user can check upon availability/waiting time for the phantoms online. National coordinators are rotating the responsibility for updates in the library and for verifying that the physical status of the library items corresponds with the online information at the website

4. The phantom used for the intercomparison exercise

The phantom IRINA (RIISH/STC, 1995) is comprised of tissue equivalent blocks of polyethylene and uses only solid source components, which reduces the risk of contamination during transport. The scattering blocks of the phantom with rod radionuclide sources inserted in the through holes form modules of one-piece or half- piece radioactivity. The radioactive material in the rods is an active powder (^{40}K) or sand coated with active resin (^{137}Cs), encapsulated in plastic rods 165 mm long and 6 mm in diameter. The activities of the sets of rods have been certified by Mendeleyev Institute for Metrology (VNIIM, www.vniim.ru), which holds the primary standard for the unit of activity of radionuclide sources in the Russian Federation.

The target activities were those corresponding to the configuration P5 of IRINA. This size of the phantom represents a standard man weighting 77.8 kg. The number of blocks for configuration P5 of the phantom is given in Table 2. The activity is considered homogenously distributed when the mounted phantom is completely loaded with the radioactive rods.

Table 2: Number of scatter blocks to mount the configuration P4 & P5 of the phantom IRINA

	P4 (61.5 kg)		P5 (77.8 kg)	
	Big blocks	Small blocks	Big blocks	Small blocks
Head & Neck	4	2	4	2
Chest	20	-	20	12
Arms	8	-	8	-
Abdomen	13	-	14	8
Thighs	14	-	14	10
Legs	10	-	12	4
Total	69	2	72	36

One of the participants requested to mount the geometry P4 which is smaller than P5, because of space constraints. The weight of P4 is 61.5 kg and the number of blocks for this configuration is also given in Table 2. The certified activities for both P4 and P5 sizes of the phantom have as reference date 1996-08-01 and are given in Table 3. These values are given with a combined standard uncertainty of 5 % at the 95 % confidence level. The half-life of K-40 and Cs-137 are 1.28 Gyr and 30 yr respectively.

Table 3: Certified activities for configuration P4 and P5 of the Irina phantom

Radionuclide	Activity (Bq)	
	P4	P5
Cs-137	33900	43600
K-40	5660	7270

5. Method for data analysis and evaluation of measurement performance

The participants were asked to perform stability measurements and activity determinations together with the corresponding measurement uncertainty, for the phantom loaded with the set of rods of Cs-137 and the set of rods of K-40. They were also asked to report the minimum detectable activity.

For stability, 5 repeated measurements had to be done without moving the phantom. A report on the gross and net counts in the ROI for K-40 was requested for each replicate measurement. The observed precision in percent was estimated as:

$$OP = \frac{\sqrt{\sum_{i=1}^{N} \frac{(C_i - M)^2}{N-1}} \cdot 100}{M} , \qquad (1)$$

where, OP is the observed precision; N is the number of repeated measurements, in this case is five; C_i is the counts observed at measurement i; M is the mean of the set of five measurements. All values were normalized to a measurement time equal to 1800 seconds.

The z-score and u-score tests were run as biasing and significance tests. The reports are also evaluated regarding the values of maximum acceptable bias (MAB) and the limit of acceptable precision (LAP). MAB and LAP in this proficiency test exercise have been set taking into account the complexity of the measurement and the many sources of uncertainty in the process. The evaluation parameters MAB and LAP are shown in Table 4.

Table 4: Values for the maximum acceptable bias (MAB) and the limit of acceptable precision (LAP) applied in this proficiency test.

Radionuclide	MAB (%)	LAP (%)
Cs-137	20	20
K-40	20	20

For the z-score testing, each reported result is converted to the corresponding value of z in the standard normal distribution. The standard normal distribution has a mean of 0 and a standard deviation of 1. Thus, the z-score is a measurement of the deviation, in standard deviation units, of the result from the true value. The z-score is determined as:

$$z = \frac{(x - X)}{s} , \qquad (3)$$

where, x is an individual reported result decay corrected to the date of the reference activities, (1996-08-01) X is the true value, i.e. the certified activity and s is the estimate for the variation of the true value, which is its standard deviation. The z-score is interpreted as: if $|z| \leq 2$ the result is considered satisfactory, if $2 < |z| < 3$ the result is considered questionable and if $|z| \geq 3$ the result is considered unsatisfactory. Also, $2 < |z| < 3$ can be considered as a warning value, i.e. a revision of the result is desirable (Thompson M. et al., 2006).

The *u*-score is about whether the reported value is significantly different from the target at a given level of probability. The quantity u is compared with critical values of the t-statistics tables. The choice of significance level is 95 % and it was known that at least three measurements have been done for reporting a value as an average. That gives a table value equal to 3.18 (Taylor J.K., 1990). The *u*-score is determined as:

$$u = \frac{|x-X|}{\sqrt{\sigma_x^2+s^2}}, \tag{4}$$

where, x is an individual reported result, X is the true value, that is the certified activity, σ_x is the standard deviation of the result based on its reported combined standard uncertainty and s is the standard deviation of the true value.

Two other parameters for evaluation of the accuracy of the reported values are defined as:

$$A1 = |x - X| \text{ and}$$
$$A2 = 2.58\sqrt{unc_x^2 + unc_X^2} \tag{5}$$

where *unc* are the combined uncertainties at the 68 % confidence level for the report from the participant laboratory and the certified value, respectively.

Precision is evaluated according to:

$$P = \sqrt{\left(\frac{unc_x}{x}\right)^2 + \left(\frac{unc_X}{X}\right)^2} \cdot 100 \quad (\%). \tag{6}$$

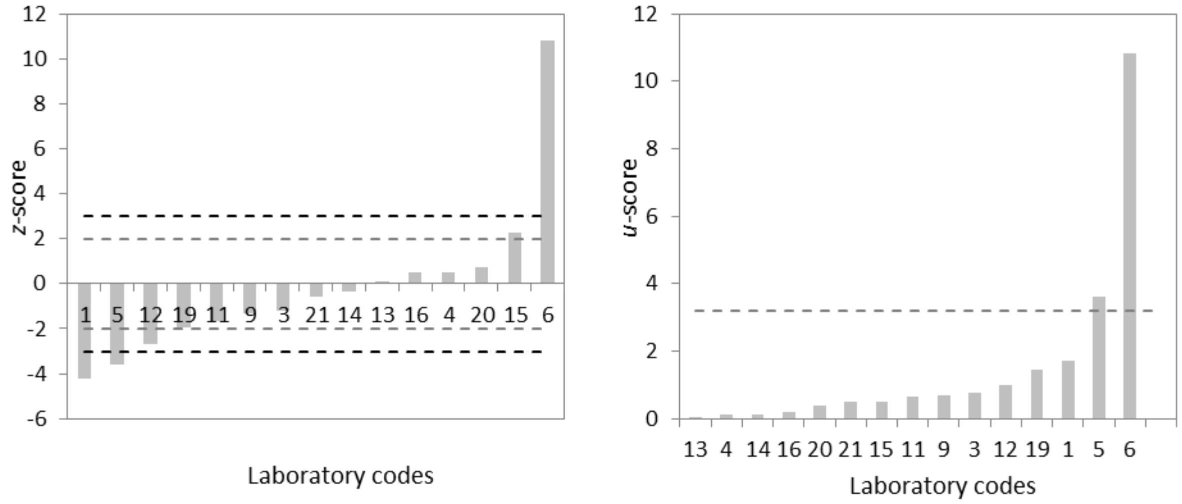
The result is acceptable for trueness if $A1 \leq A2$ and acceptable for precision if $P \leq$ LAP, see Table 3. A combined evaluation of trueness and precision is done by setting the mark **A** (acceptable) if both criteria for trueness and precision are met, **N** (not acceptable) in the opposite case, when neither trueness and precision criteria are fulfilled and **W** (warning) in the case when only one of the criteria is met, given that the relative bias is below MAB. The relative bias in percent is $100 \cdot A1/X$.

The instruction for providing the minimum detectable activity (MDA) at the 95 % confidence level was to report the activity of K-40 and Cs-137 from measurements of the phantom not containing radioactive rods. The MDAs are then $MDA_{K40} \cong 3\sqrt{x0_{K40}}$ and $MDA_{Cs137} \cong 3\sqrt{x0_{Cs137}}$, where $x0$ are the “blank” activities for K-40 and Cs-137, respectively.

6. Results and discussion

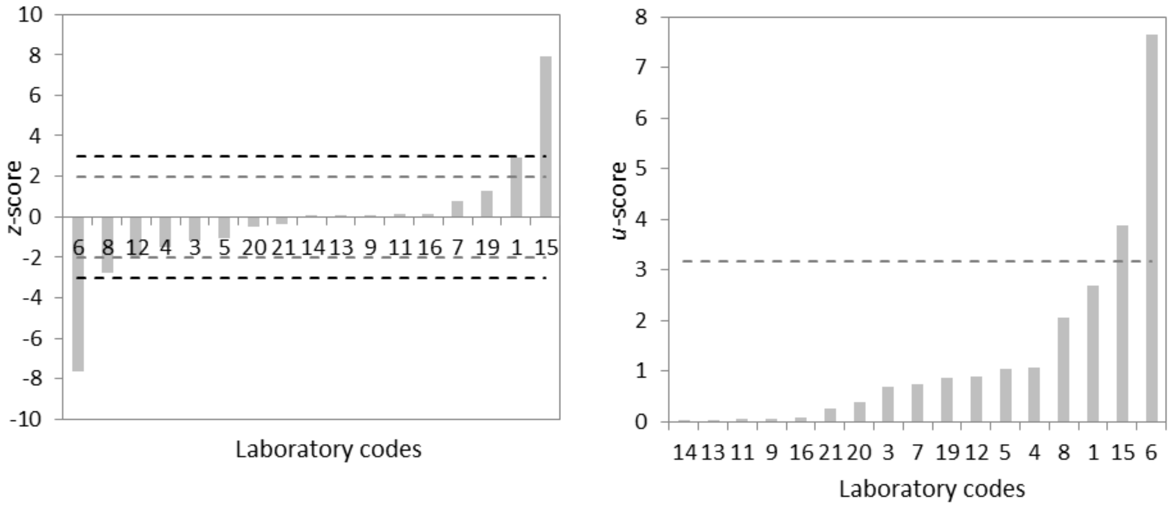
The repeatability tests showed good stability for all the participant’s measurement systems. The observed precision (OP) has been compared to the Poisson precision (PP). The Poisson precision, in percent is: $PP = \sqrt{M} \cdot 100/M$. Unity would be the ideal value since it is well know that radioactive decay is governed by Poisson statistics and so the ideal counter should theoretically have precision close to Poisson precision. The average of the set of all the gross count reports was 1.3. Most of the participants submitted gross count data with precision behavior close to Poisson and within two standard deviations of the mean of the reported data.

Results for the *z*- and *u*-scores are shown in Figures 1 & 2. Laboratories 7 and 8 didn’t submit results for the activity of K-40. For K-40, the *z*-score testing showed three laboratories, 1, 5 and 6, with non-acceptable results, that is, $z > |3|$ and two with questionable results $|2| < z < |3|$. The *u*-testing showed, with 95 % confidence, that laboratories 5 and 6 reported activity values significantly different from the certified reference activity for K-40.



a) b)

Figure 1. a) Biasing *z-score* testing for the reported activities of K-40. b) Significance *u*-score testing for the reported activities of K-40.

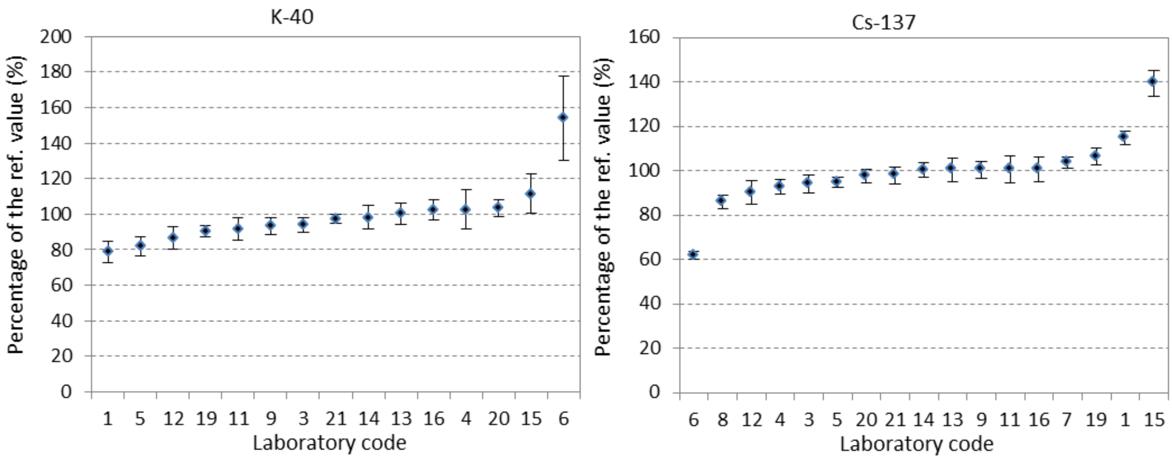


a) b)

Figure 2. a) Biasing *z*-score testing for the reported activities of Cs-137. b) Significance *u*-score testing for the reported activities of Cs-137.

For Cs-137, the z-score testing showed two laboratories, 6 and 15, with $z > |3|$ and two with questionable reports $|2| < z < |3|$, figure 2a). The *u*-score testing showed also that laboratories 6 and 15 reported activity values significantly different from the certified reference value, figure 2b).

The plot ranking the accuracy of the reported values shows the results in percentage of the reference value in Figure 3a), for K-40 and in Figure 3b), for Cs-137. The 100 % line represents the true value. Most of the participants reported activity values within the acceptable bias.



a) b)

Figure 3. a) Relative bias for the reported values for the activity of K-40. b) Relative bias for the reported values for the activity of Cs-137.

A combined evaluation is presented in Table 4. The reported uncertainty corresponds to the total combined uncertainty reported at one sigma, that is, with 68 % confidence. The comparison has been performed between the reported values and the certified values, corrected for radioactive decay to the date of the measurement, for each participant laboratory. Laboratories 5 and 6 didn't report the values for the combine standard uncertainties and therefore the evaluation was done only based in the relative bias of the reported activities with respect to the certified reference values.

The combined evaluation is consistent with the results of the tests run for significance and biasing scores (*u*- and *z*-score). Two laboratories didn't meet the reference values. Laboratories 5 and 6 reported non acceptable results for K-40 and laboratories 6 and 15 for Cs-137. Non acceptable performances are basically connected to inadequate calibration of the measurement system. Therefore, an obvious outcome from this proficiency test has been the recommendations to these laboratories to re-calibrate their systems.

The result accepted with a warning could reflect either a result with small measurement uncertainty that has a relative bias still within the accepted interval. It could also be a result that is within the accepted interval for biasing and even closer to the target than in the first situation but the reported uncertainty is large. The laboratories giving acceptable reports, but with a warning, were labs 1 and 4 for K-40, and labs 5 and 12 for Cs-137. These laboratories should review the uncertainty budget and eventually engage in re-calibration.

The detection limits for the determination of K-40 ranges from 40–10000 Bq and for Cs-137 from 20–900 Bq. That a larger counting time gives lower MDA is the trend verified for laboratories with similar measurement geometry and detectors. In general, it was observed that the laboratories equipped with NaI detectors or combined measurement systems with NaI together with plastic scintillators and/or HPGe detectors showed the lowest MDAs. Also, the systems with more than one detector showed, in general, smaller MDA values than the systems with only one detector.

7. Conclusions

The proficiency test in the framework of the PIANOLIB activity was successfully completed with a satisfactory level of participation. From a total of 21 measurements systems registered from nineteen laboratories, we received reports from 17 measurement systems in fifteen laboratories, that is, 81 %. All participating laboratories were able to quantify the activity of Cs-137 and 15 quantified the activity of K-40. It should be pointed out that the target activity for K-40 was as low as encountered naturally in the human body, which is challenging.

Table 4: Combined performance evaluation for the determination of K-40 and Cs-137.

Laboratory code	Reported values K40		Performance score for K-40	Target values decay corrected for Cs-137		Reported values Cs137		Performance score for Cs-137
	Act.(Bq)	unc(Bq)		Act. (Bq)	unc (Bq)	Act. (Bq)	unc (Bq)	
1	5744	821	AW	31796	1590	36452	696	A
3	6830	440	A	31738	1587	29900	2100	A
4	7464	1573	AW	31710	1586	29368	1482	A
5*	4640	-	NA	24579	1229	23300	-	AW
6	11200	-	NA	31558	1578	19500	-	NA
7**	-	-	-	31530	1576	32700	1000	A
8**	-	-	-	31502	1575	27100	1450	A
9	6790	600	A	31446	1572	31600	1900	A
11	6670	860	A	31385	1569	31600	3600	A
12	6300	900	A	31268	1563	28200	3100	AW
13	7300	800	A	31268	1563	31400	3100	A
14	7140	910	A	31235	1562	31300	1300	A
15	8100	1563	A	31205	1560	43520	2770	NA
16	7444	772	A	31178	1559	31426	3143	A
19	6560	330	A	31083	1554	33070	1700	A
20	7530	600	A	30978	1549	30220	1200	A
21	7070	150	A	31417	1571	30800	1900	A

* Laboratory 5 used Irina geometry P4
** Laboratories 7 and 8 didn't participate in the determination of K-40

Most of the participants were able to quantify correctly the activities of K-40 and Cs-137 and the overall performance is equally good as the results of a previous exercise of this kind performed in 2004 (Rahola T. et al., 2006). The problems experienced by laboratories which submitted non-acceptable results could generally be attributed to the calibration of their systems.

The results of the proficiency test were presented and discussed at a Workshop, organized within the framework of the activity and held at the University of Gothenburg, September 15th and 16th 2011. The conference offered all participants an opportunity for getting insights and exchange of experiences. All the presentations given at the Workshop are available at the NKS website (NKS-B Seminars, 2011).

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