D3S – results of qualification measurements of a wearable RIID for homeland security

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1 ABSTRACT

A testing facility for qualification tests of measurement devices for radioactive and nuclear material was established at the Fraunhofer INT. This was done in the framework of the Illicit Trafficking Radiation Detection Assessment Program + 10 (ITRAP+10). The test methods were developed in the program based on ANSI and IEC standards. After the completion of the setup of the facilities, they are now used for testing of various devices.

This paper deals with tests in accordance with the ITRAP test procedures and the corresponding results obtained for the D3S detector from Kromek. The device is designed to be used as radiation isotope identifier (RIID) as well as personal radiation dosimeter (PRD). Therefore tests referring to test methods for both types of devices were performed. The device contains a cesium iodine gamma as well as a non-helium-3 neutron detector, and both kinds of sources were used for the device qualification.

The tests are divided in tests of general requirements, radiological tests, and radionuclide identification tests. For example, the tests of general requirements include tests of the user interface, battery requirements, documentation, or audible and vibrational alarm. The radiological tests comprise tests concerning false identification rate, time to alarm, accuracy tests for photons, over range, and gamma response of the neutron detector. The quality of the nuclide identification results is part of the radionuclide tests.

Partly the requirements for PRDs and RIIDs are identical, partly not. For example, the time to alarm value in which an alarm shall be created after the device is exposed to the source is 2 s for PRDs and 3 s for RIIDs, respectively.

The D3S passed many tests, but also failed some. The tests also showed the limits of such test procedures. They are standard tests under fixed conditions whereas in reality different situations occur in which the obtained results may not turn out as well as the tests indicate.

The paper presents results of the qualification tests done with the D3S as well as a suggestion for an additional close to reality test.

Key words: test procedure for nuclear and radioactive measurement devices, illicit trafficking, neutron sources, gamma sources, D3S, RIID, PRD

2 INTRODUCTION

The qualification tests obtained at the Fraunhofer INT test facility [1], [2] are in accordance with the ITRAP + 10 test methods and will be introduced in the next section 3. Section 4 gives an overview of the system D3S, which is to be tested, and its operation. The measurement setup in the test facility summarizes section 5. The results obtained during testing are presented in section 6.

3 ITRAP+10 TEST METHODS

The device was tested in relation to the test procedures for two types of device; for Personal Radiation Detector (PRD) and Radiation Isotope Identifiers Device (RIID). The different tests in the radiological categories are given in this chapter. The test procedures are part of the results obtained by means of the ITRAP+10 project [3] and base on the IEC and ANSI standards. Different sources shall be used for the tests. To cover a wide gamma energy range ^{241}Am, ^{137}Cs, and ^{60}Co sources are used for all radiological tests except the identification tests where additional nuclides are used. For the neutron tests a ^{252}Cf source is used. The source is always surrounded by 5 mm lead and 1 cm steel. A phantom representing a user is used for both types of devices according to the operational purpose. The phantom consists of PMMA and has a size of 30 cm x 30 cm x 15 cm, for the PRD tests the device is fixed on the surface of the phantom representing the body of the user carrying the PRD. For the RIID tests the surface of the phantom is 50 cm behind the RIID device, representing the body of the person with the device in hand, held at an arm's length.

3.1 False identification tests

The instrument shall not identify nor give an alarm in a stable ambient radiation background environment. For the PRD in a 10 h time period there shall be less or equal to one gamma and neutron alarms. For the RIID devices in 30 trials of one minute each, no radionuclide shall be identified that is not present (other than natural occurring material (NORM)).

3.2 Time-to-alarm photons and neutrons

The instrument shall alarm when the radiation is increased from background level to a radiation level above the alarm level of the device. In case of the PRD and RIID devices, the increase shall be 0.5 µSv/h in 0.5 s or less. The alarm shall be within 2 seconds for the PRD and within 3 seconds for the RIID.

3.3 Accuracy tests for photons

The displayed ambient dose equivalent rate indication shall be within ± 30 % for dose equivalent rates of 0.5 µSv/h, 5 µSv/h and 50 µSv/h for PRDs, and in addition for 100 µSv/h for RIIDs .

3.4 Over-range characteristics for ambient dose equivalent rate indication

The device shall indicate an over-range when being exposed to an ambient dose equivalent rate above the stated maximum dose rate. The indication shall stay for the whole exposure time. Within 5 min after the end of exposure the instrument shall have recovered and function normally. For the PRD devices the test shall be started with 100 µSv/h, successively increasing the dose rate until an over range indication appears. In case of the RIIDs the dose equivalent rate shall be increased to twice the value of the manufacturer-stated maximum up to a maximum of 1 mSv/h. In both cases the indication shall be within 5 s of a dose rate step change.

3.5 Gamma response of a neutron detector and neutron response in the presence of gamma

The test comprises two aspects. Firstly, the neutron detector shall not indicate any neutrons when being exposed only to a high gamma dose rate (100 µSv/h, ^{137}Cs). And secondly, if being exposed to a high gamma field and an additional neutron source, the device shall indicate neutrons.

3.6 Radionuclide Identification

The identification measurements are divided in single radionuclide identification, mixed radionuclide identification, masking, and interfering beta radiation.

For single radionuclide identification, the instrument shall be able to identify radionuclides increasing the ambient dose equivalent rate at least to 0.5 µSv/h above background. Without shielding the radionuclides shall be identified in 1 minute (^{40}K, ^{57}Co, ^{60}Co, ^{67}Ga, ^{99m}Tc, ^{133}Ba, ^{137}Cs, ^{201}Tl, ^{226}Ra, ^{232}Th, ^{241}Am, high enriched uranium (HEU) and weapon grade Plutonium (WgPu)), and behind 5 mm steel shielding in 2 minutes (^{40}K, ^{57}Co, ^{60}Co, ^{67}Ga, ^{99m}Tc, ^{133}Ba, ^{137}Cs, ^{201}Tl, ^{226}Ra, ^{232}Th, ^{241}Am, HEU and WgPu).

The second as well as the third test have the focus on special nuclear material (SNM). For the mixed identification ^{137}Cs and HEU, ^{57}Co and HEU, and ^{133}Ba and WgPu shall be identified correctly. For the masking tests the instrument shall provide an indication when exposed to a radionuclide masked by another radionuclide that is not listed in the library or that has much higher radiation intensity than the masked radionuclide. Therefore masking scenarios with nuclides of similar energy lines can be tested (SNM + medical isotopes, e.g., ^{67}Ga or ^{99m}Tc masking HEU, SNM + industrial isotopes, e.g., ^{137}Cs masking Pu) as well as those with different energy lines (SNM + NORM material).

One problem concerning these tests, however, is that the availability and possession especially of SNM material is regulated.

4 TEST SYSTEM

The D3S is equipped with two embedded scintillators; CsI(Tl) for gamma-ray detection and a Helium-3 free neutron component utilizing Lithium. It is a wearable device which can function as PRD as well as RIID. Especially for the PRD purpose it consists of two parts, a detection device and a smartphone (see Figure 1).

Figure 1: Test system D3S. <u>Left:</u> detector part, <u>Right:</u> smartphone with measurement results upper part: search mode in which the PCS significance over time is displayed; lower part: Confirmation ID-mode in which the energy spectra is displayed. On the smartphone the right side shows the text box with status information, alerts, and measurement results.

The detection device can be worn on the belt where data transfer to the smartphone is provided via Bluetooth. The front side visible in Figure 1 shall be worn on the surface, therefore that side of the detection device pointed towards the sources while testing.

Two modes are implemented: search mode and confirmation (ID) mode. Both modes give an identification result (see Figure 2). In the search mode a new measurement result is displayed every second, it gives a 3 s rolling average. The confirmation (ID) mode obtains measurements for 30 s. These times are fixed and cannot be changed.

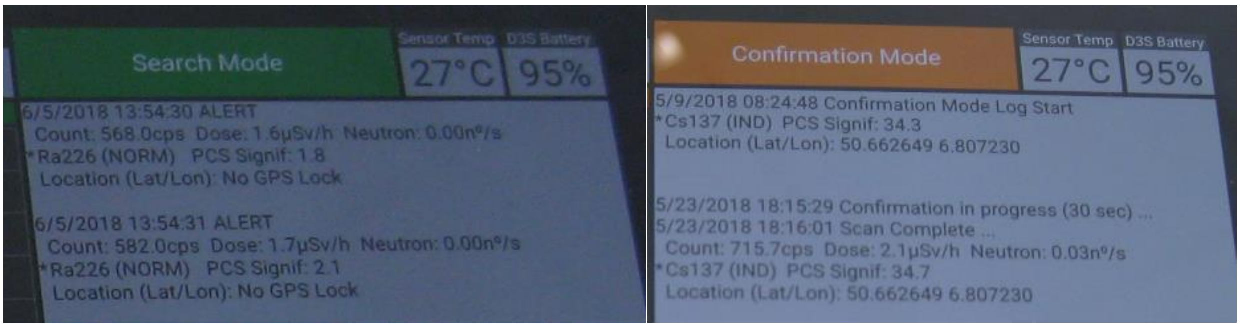

Figure 2: Result output. <u>Left:</u> Search mode, result is given every second <u>Right:</u> Confirmation (ID) mode, result is given after 30 s measurement time. The information is: γ- and n-count rate, dose rate, identified nuclide with corresponding PCS significance and the location.

According to the manufacturer, the PCS significance is related to the confidence level.

The measurement results are given in the text box. The alarm is given as vibration signal and spoken text by the smartphone as well as in text form. In the confirmation mode example of Figure 2 the acoustic information is: “Alert, caesium-137 is detected”. In other cases with gamma count rates of above 2000 cps it will be “Alert, high gamma count” and above 10000 cps “Alert, gamma count over range”. In the latter two cases no identification result will be gained.

During the tests presented the device was used with the ID App version 1.3.5., search mode library version 1.0 and confirmation mode library version 1.0.

5 MEASUREMENT SETUP

Qualified tests which lead to reliable results require an appropriate measurement setup. In order to qualify measurements devices of different classes according to their corresponding standards, we intended to perform both static and dynamic measurements. In this paper, we concentrate on static measurements. The setup has already been described before in [1]. The setup used for the presented results is shown in Figure 3.

The D3S consists of two parts. One part is the detector unit; the other part is the control, display and evaluation unit (smartphone). For the tests the smartphone in general could had been placed anywhere in the range of the Bluetooth communication signal. But in order to be able to simultaneously record the results displayed on the smartphone and the status of the radiation source it had to be placed in view of one of the video cameras of the testing system.

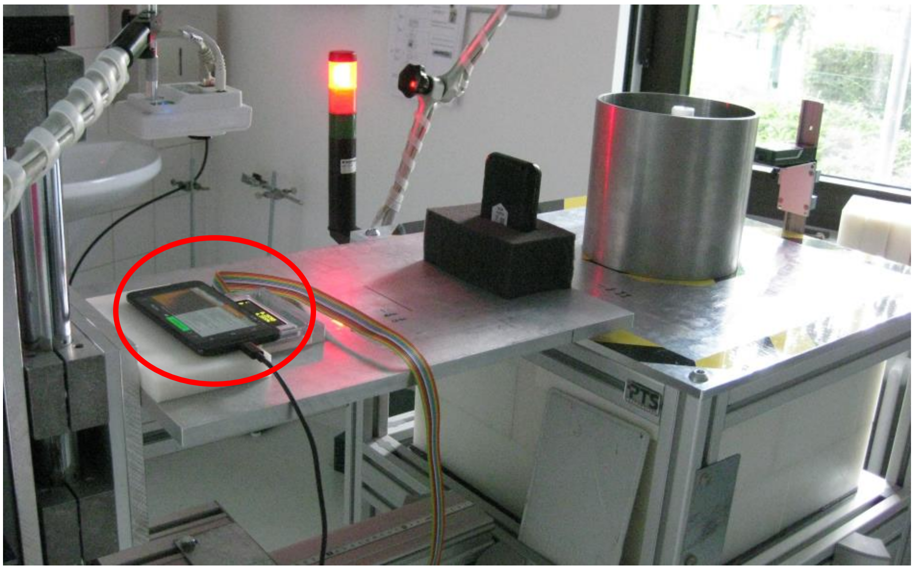

Figure 3: General setup of the static measurement system. D3S smartphone and clock display of the measurement system (inside the red circle), with camera for data recording on the left (corresponding image of the camera see Figure 4); D3S device placed inside a hold in the center, and the source behind a shield of steel on the right.

In order to examine the time behavior of the measurement devices a time measurement system is needed. The used clock is started and stopped automatically by the pneumatic system that lifts and lowers the sources. The time information of this pneumatic system is displayed and can be seen in Figure 4.

Figure 4: Image of the camera as positioned in Figure 3: Clock display (above) with rows from bottom to top: current time in the upward position (U), time for downshift, time in down position (D), time for upshift; below: display of the D3S smartphone in confirmation mode.

6 TEST RESULTS

As the D3S can either function as a PRD or as a RIID it was tested with the procedures for both device classes. The first tests according to the PRD test procedure were the false alarm and time to alarm tests as already described in [1].

6.1 Accuracy test for photons

The tests were performed with ^{60}Co, ^{137}Cs and ^{241}Am under the above mentioned conditions (see chapter 3). The result is summarized in Table 1. Only for the PRD requirements with ^{60}Co the test was passed.

A detailed result for ^{241}Am is given in Figure 5. D3S dose rate measurement results are plotted versus the correlating dose rate results measured with the calibrated reference device MAB 500. The expected behavior of the data points would be a bisector which is given in red. Only the measurement at about 50 µSv/h was within the ± 30 % region of the value measured with the reference detector. Even taking the uncertainty of the reference detector of ± 20 % into account would not lead to better accordance.

	PRD	RIID
^{241}Am	✘	✘
^{137}Cs	✘	✘
^{60}Co	✓	✘

Table 1: Results of accuracy test for photons for both modes (PRD and RIID); ✘ refers to a failed test, ✓ for a test which was passed.

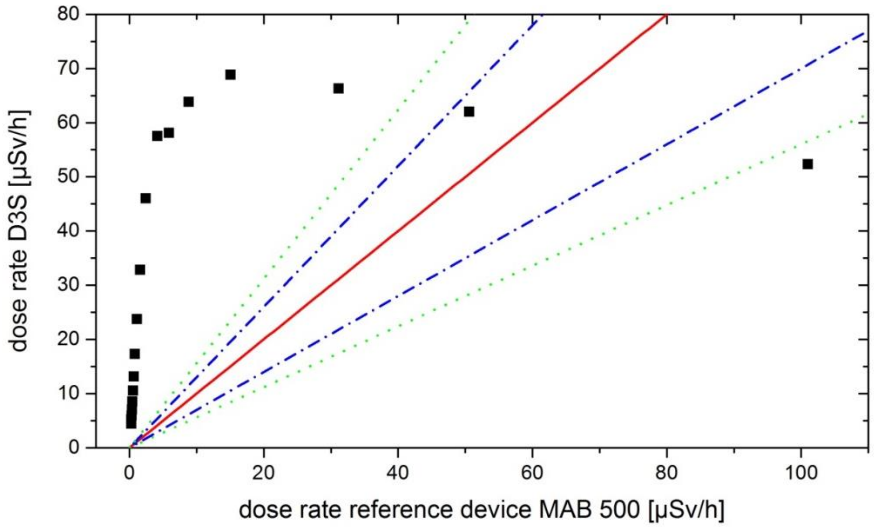

Figure 5: ^{241}Am source measured in different distances with the D3S and the reference device MAB 500. The solid red line gives the expected behavior with D3S results equals MAB 500 results, the blue dashed lines refer to a deviation of ± 30 % to the MAB values, the green dotted lines to MAB 500 values taking an additional deviation of ± 20 % into account.

The estimation of dose rate values is problematic with the D3S, especially for low energy gamma-ray sources. Although PRDs and RIIDs are not primarily intended for dose rate measurements and explicitly not in the context of radiation protection, the extremely too high dose rates for ^{241}Am given by the D3S and the falling values with true dose rates greater than 20 µSv/h also lead to other difficulties, e.g., the D3S would never show over range when facing a high activity ^{241}Am source. This erratic behavior is not covered by current over range test procedures. Therefore great care should be taken if a performance parameter like the dose rate accuracy would possibly be regarded as “not so important” for such a device primarily intended for search and identification.

6.2 Identification

Identification tests have been performed with several isotopes without and with 5 mm steel: ^{241}Am, ^{133}Ba, ^{152}Eu, ^{57}Co ^{60}Co, ^{137}Cs, ^{226}Ra, ^{232}Th, ^{99m}Tc. The nuclides ^{57}Co, ^{60}Co and ^{137}Cs

were identified correct in both cases; with and without the additional 5 mm steel shielding. Thereby here only the results obtained using the confidence mode with the preset 30 s acquisition time were taken into account. For a detailed discussion of the results for the measurements with ^{99m}Tc, see section 6.4.

In the other cases some problems with the measurements with shielding occurred. For example with ^{226}Ra: two subsequent repeated 30 s measurements with steel shielding yielded quite different results. The results given in the text box of the confirmation mode are shown in Figure 6. The first measurement gave ^{137}Cs and ^{131}I. The second measurement, however, yielded ^{131}I along with ^{60}Co. In further measurements also ^{192}Ir was given as identification results. The first measurements the PCS Significances might be taken as not that secure, but this is not further indicated. The nuclides marked with are star (*) are displayed in the Detection/ID part of the display and announced acoustically.

The measurement without steel shielding in the confidence mode showed ^{226}Ra as single result. For the measurement in Search mode ^{133}Ba, ^{131}I, and ^{192}Ir were also given after 3 s. Due to the short measurement interval during changing measurement situation generally speaking the results obtained in the search mode should be analyzed with care.

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6/19/2019 11:45:21 Confirmation in progress (30 sec) …
6/19/2019 11:45:54 Scan Complete…
 Count: 519.8 cps Dose: 1.5 µSv/h Neutron: 0.00 n°/s
*Cs137 (IND) PCS Signif: 5.5
 I131 (MED) PCS Signif: 2.8
 Location (Lat/Lon): 50.662899 6.807819

6/19/2019 11:48:59 Confirmation in progress (30 sec) …
6/19/2019 11:49:28 Scan Complete…
 Count: 513.5 cps Dose: 1.5 µSv/h Neutron: 0.00 n°/s
 Co60 (IND) PCS Signif: 2.2
*I131 (MED) PCS Signif: 13.5
 Location (Lat/Lon): 50.662899 6.807819
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Figure 6: D3S result in confirmation mode obtained with a ^{226}Ra source shielded with 5 mm steel. Two consecutive repeated measurements.

It was tried to perform the measurements for all nuclides with comparable conditions. The ITRAP test procedure foresees a minimum dose rate for the tests of 0.5 µSv/h above background level. We chose 1.5 µSv/h, this value was adjusted using the reference device MAB 500. The accuracy problems which have been observed during the tests lead to difficulties with the ^{241}Am identification tests (see section 3.3). The D3S gave much too high values which lead to count rates of above 2000 cps. As this is the limit for identification measurements, no identification result could be gained for ^{241}Am during the measurements of the unshielded sources. A decrease of the distance to reach count rates below 2000 cps allowed correct identification results in all cases. Though now the dose rate was only 0.36 µSv/h measured with the reference device which is not in the foreseen region.

6.3 Mixed sources

In an additional test, the D3S was exposed to a combination of four sources simultaneously: ^{60}Co, ^{133}Ba, ^{137}Cs, and ^{152}Eu. This is shown in Figure 7.

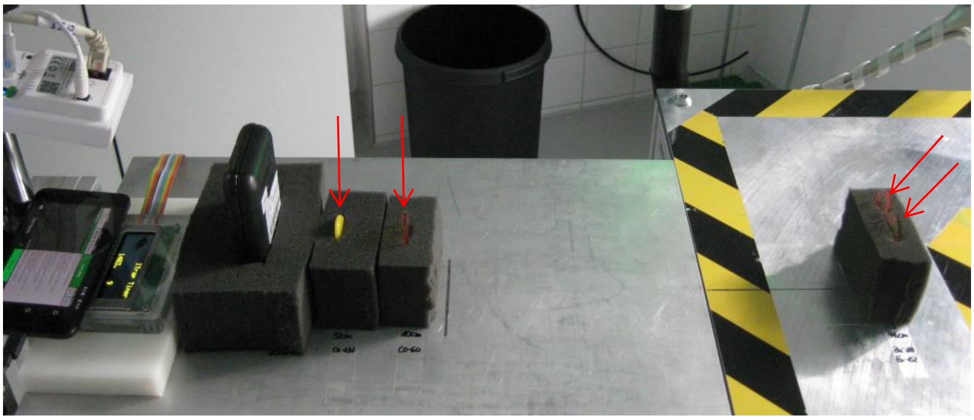

Figure 7: D3S on the left, the sources (marked with red arrows) on the right were placed at different distances to the device in order to create similar values of the dose rate at the detector's position.

An example is given in Figure 8 which shows the identification results of the measurement performed in confirmation mode. In this mode ^{133}Ba, ^{60}Co and ^{137}Cs were always identified whereas ^{152}Eu was never identified. During the 3 s measurements in the search mode ^{152}Eu was identified in some of the measurements. However, the acoustic announcement of the identification result merely stated one of the nuclides present during each measurement depending on the higher PCS significance without any hint of others being present. This is not optimal when thinking of moving around without looking at the display all the time.

Figure 8: Example of measurement result in Confirmation Mode. ^{60}Co has the highest PCS Significance with 16.6 and is given as result and is given acoustically, ^{133}Ba and ^{137}Cs are identified too.

6.4 ^{99m}Tc - moving device

The measurements performed with ^{99m}Tc are characterized by the short half live of the nuclide (6 h) and therefore fast changing measurement conditions. Tests have been done on a person who incorporated ^{99m}Tc and a urine probe without and with 5 mm steel shielding. Due to those circumstances the tests could not be performed at the Fraunhofer INT test facility and not in compliance with the number of trials given in the test procedure. The identification test results obtained are listed in Table 2.

In general ^{99}Tc was identified although it was not marked as metastable. According to the manufacturer "Tc99" is a spectrally perturbed ^{99m}Tc. Partly "*Tc99med" and "Tc99med" were given as identification result. The meaning of the prefix * as well as the doubled Tc output is unclear. During the first measurements shielded with 5 mm steel ^{123}I was given as result too.

The urine probe was tested at a shorter distance between detector and source. It was chosen to stay below 2000 cps (measured by the D3S) in order not to be in the high gamma count rate region. While setting the distance the device was moved starting rather close with a count rate above 2000 cps. While pulling back the device ^{57}Co (IND) was identified in a reproducible way prior to ^{99}Tc (MED). The γ-energy of ^{99m}Tc is 140 keV (single line), whereas the main γ-energy of ^{57}Co is 122 keV (85.9 %) and only a smaller part of the emission is in the same energy region as ^{99m}Tc: 136 keV (10.3 %).

<table>
<tr><th rowspan="2">time [min]</th><th rowspan="2">count rate D3S [cps]</th><th rowspan="2">shielding</th><th colspan="3">identification result</th></tr>
<tr><th>search mode</th><th colspan="2">confirmation ID mode</th></tr>
<tr><td>0</td><td>1000 ± 50</td><td>-</td><td>*Tc99 med</td><td colspan="2">*Tc99med</td></tr>
<tr><td rowspan="2">15</td><td rowspan="2">400 ± 50</td><td rowspan="2">5 mm steel</td><td rowspan="2">*Tc99 med
Tc99 med</td><td>I123 med
*Tc99 med</td><td>5/11</td></tr>
<tr><td>*Tc99 med
Tc99 med</td><td>6/11</td></tr>
<tr><td>295</td><td>470 ± 50</td><td>-</td><td>*Tc99 med</td><td colspan="2">*Tc99med</td></tr>
<tr><td>285</td><td>230 ± 50</td><td>5 mm steel</td><td>*Tc99 med
Tc99 med</td><td colspan="2">*Tc99med</td></tr>
<tr><td>330</td><td>1900 ± 50</td><td>-</td><td>*Tc99 med
Tc99 med</td><td colspan="2">*Tc99med</td></tr>
<tr><td>310</td><td>1800 ± 100</td><td>5 mm steel</td><td>*Tc99 med</td><td colspan="2">*Tc99med</td></tr>
</table>

Table 2: Identification results obtained with the D3S measuring ^{99m}Tc incorporated in a person. Time zero minutes is when performing the first measurements. The first four measurement series have been performed at the same distance, the latter at a distance to have less than 2000 cps. The identification results are given as displayed. There is no explanation for the*. According to the manufacturer labelled Tc99 is a spectrally perturbed Tc99m. For the measurements starting after 15 min two different results were obtained in the confirmation ID mode, the numbers are given with regard to the performed 11 measurements in that case.

6.5 Gamma sensitivity of neutron detector

For these measurements a different setup was required and for neutron measurements in general a PMMA phantom is used. For PRD measurements, the device was placed on the PMMA, representing the wearer‘s torso. For the RIID measurements, the PMMA was positioned 50 cm behind the device as it is usually thought to be carried in hand while the user’s arm is outstretched.

Figure 9: Setups for gamma sensitivity measurements of the neutron detector; left: PRD measurement setup, right: RIID measurement setup; the orange container houses the ^{137}Cs source.

The D3S passed both tests as no neutrons were displayed when being exposed to a strong gamma source. A ^{137}Cs source produced 100 µSv/h at the position of the device.

7 CONCLUSIONS AND FURTHER RECOMMENDATIONS

In search mode the D3S gives identification results rather fast. However in the beginning of a test situation or when the test situation changes rather fast, the results would have to be looked into more closely. In view of this, background effects from a slowly approaching source should be tested as well as the temporal development of the search identification result under varying count rates. The latter shall be realized by moving sources or a moving device. This corresponds to the real situation where a person walks around and gains identification results in search mode.

Indicated dose rate values should be handled with care and the D3S's performance in this respect needs further investigation.

In the ITRAP+10 test procedures dynamic tests are foreseen only for the PRD devices, not for the RIIDs. In comparison, the IEC standard for Spectroscopic Personal Radiation Detectors (SPRDs) [4] as well as the ANSI requirements for SPRDs comprise a test for the detection of gradually increasing radiation levels [5]. In the latter requirements for SPRDs and in the ANSI requirements for handheld instruments for the detection and identification of radionuclides [6] a dynamic test for photon and neutron alarm or indication is included. However, the tests in those test procedures do not focus on identification, but only on the alarm itself.

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