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In Situ, Rapid Inspection Methods for Radioactive Material Transportation²

Radioaktív szállítmányok gyors, in situ ellenőrzési módszerei

Radioactive materials are shipped in most countries within the framework of regulations and laws. In almost all cases the supervision of the shipments is in the hands of governmental organisations. In situ checks during shipment cover several areas, but it is usually limited to checking the shipping documents and packaging. There is no quick and easy field-based method for verifying the content of the documents. This inspection method helps to detect rough differences between data written in shipment documents and in reality. As a result of the inspection, the officer will know, whether it is worth investigating further or not. The method contains multiple measurements made by intelligent detectors. Unknown values like activity of the transported source and shielding efficiency of the container can be estimated with the help of incoming measured values combined with the information from the shipment documentation. The method was confirmed with real Cs-137 source and with an isotope container.

Keywords: radiation measurement, detection, radioactive transport, intelligent detector, ADR class 7, activity determination

Radioaktív anyagok szállítása a legtöbb országban rendeletekkel, törvényekkel szabályozott keretek között zajlik. A szállítás ellenőrzése szinte minden esetben hatósági feladat. A szállítás közben végrehajtott helyszíni ellenőrzés korlátozódik a szállítmány okiratainak és a csomagolás külsejének ellenőrzésére. Arra nem létezik gyors, egyszerű, a terepen végrehajtható módszer, hogy a dokumentumokban szereplő adatokat ellenőrizni lehessen, a csomagban lévő radioaktív anyagok aktivitását meg lehessen határozni. A közleményben ismertetett módszerek segítséget adnak arra,

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hogy fel lehessen fedezni a durva eltéréseket a papíron szereplő adatok és a valóság között. A mérés eredményeként a végrehajtó állomány tudni fogja, hogy érdemes-e tovább vizsgáldni vagy nem. A módszer többféle intelligens detektorok által végrehajtott mérést tartalmaz. A módszert valós forrással (Cs-137) és egy izotóptartállyal ellenőrizték.

Kulcsszavak: sugázmérés, detektálás, radioaktív transzport, intelligens detektor, ADR 7. osztály, aktivitás meghatározása

Introduction

The purpose of this research is to find out whether the capabilities of officials responsible for controlling radioactive transport can be improved. International standards recommend checking transports with radiation detectors. The IAEA suggests using a handheld instrument that should be held against the surface of the package to measure the dose rate.³

The regulation in the EU for Dangerous Goods by Road (ADR) gives a maximum radiation limit of 10 mSv/h at any point of the package and categorises the packages according to a measured dose rate at the surface and 1 meter distance from the package.⁴

The aim of all international regulations is to have a reasonably acceptable radiation level for the personnel involved in transportation. All these levels are calculated back to the personal and collective dose limits of the current regulation. There is no intention in these regulations, to question the veracity of the information declared by the supplier. Despite the fact that an incorrectly categorised shipment can cause serious environmental damage, nuclear accident or unnecessary radiation exposure.

Basic Inspection Method

Radioactive material transportation requires a lot of documentation. In these documentations, there are some parameters, which could be the input data of an inspection. There are some parameters that can be checked easily without any measuring instruments, and there are measured parameters to validate the theoretically stated values and category levels.

The first step of a basic inspection is to collect all the available data from the documentation and check if there is any contradiction. Knowing all category levels and comparing them with the available data needs time and experience. In order to make the inspection quicker and easier, a demo application called Radiation Inspector was created. The officer has to type the data into the mobile software and the application will do the comparison.

The following information should be available in the documentation to conduct a basic inspection: Type of the radionuclide, activity of the source, the date when the activity measurement was conducted or calculated, dimension of the package (height, weight, and

³ IAEA 2012.

⁴ United Nations 2017.

diameter of the container), shielding wall thickness, material of the shielding, transport index, criticality safety index, category according to ADR rules.

After filling out a form in the mobile application, the data is stored and analysed. With the help of comparison and calculation algorithm the following potential issues can be filtered out:

- Shipment documentation contains higher activity as the allowed limits.
- The package is not categorised correctly according to ADR rules.⁵
- Stated parameters contradict each other, e.g. the volume of the container calculated from the dimension is different from the volume calculated from the weight.

Comparing data with limits is an easy task, there is no need for further explanation, but finding contradiction related to the stated source activity is more challenging. The source with the stated activity should generate a theoretical dose rate at a specified distance in the air, which is reduced by the shielding effect of the container. Equation (1) shows that the theoretical dose rate can be calculated from the activity.⁶

$$Dr = 5,77 * 10^{-4} * \frac{A}{4\pi d^2} \sum_i^n E_i P_i \left(\frac{\mu}{\rho}\right) B_i e^{-\mu x} \quad (1)$$

Dr: theoretical dose rate

A: activity of the source

d: distance between the source and virtual detector

E: gamma emission energy

P: emission probability per disintegration respectively

μ/ρ : mass absorption coefficient for tissue

x: shield thickness

μ : linear attenuation coefficient for shielding

B: build-up factor

Special parameters like the buildup factor are properties of the shielding material. If all the basic input variables (isotope type, shielding and distances) are known, all other necessary static parameters (mass absorption coefficient, gamma emission energy, etc.) are already defined by former studies and simply used by the algorithm automatically, the officer does not need to be an expert to know them off the top of his head.⁷

The theoretical dose rate can be checked by a real dose rate meter. If the measured value is in the same range as the theoretical dose rate, the validity of the activity stated in the transportation documentation is correct.

For this measurement, the most suitable instrument is a certified dose rate meter which has a wide measuring range in energy and dose rate and can be connected to a data collector

⁵ United Nations 2017.

⁶ MAGILL 2019.

⁷ CHILTON, 1967.

that can collect other parameters as well. I used the RadGM dose rate transmitter for this measurement (Figure 1), which has the energy range of 50 keV ... 3 MeV and the dose rate range of 30 nSv/h ... 10 Sv/h. The RS-485 interface and the compact size makes it ideal for this task.



Figure 1. RadGM dose rate transmitter

Source: Gamma Zrt. 2019

If the activity is unknown, it should be determined from the dose rate measured without opening the package. There are many issues that could add error to this measurement. E.g. the error of the detector, the effect of other radioactive material. It is important to establish a controlled environment for this measurement.

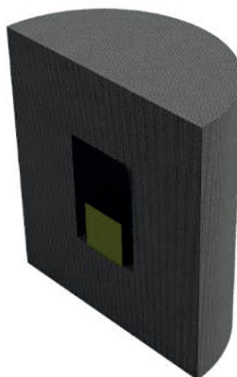


Figure 2. Schematic of a radioactive transport package

Source: Made by the author

Another problem with this measurement is that usually some of the parameters are not available in the documentation or could be incorrect. E.g. the container parameters (wall thickness, material, etc.) are not mandatory to include.

Radioactive sources are transported in different packages. High activity level sources are typically transported in cylindrical shape lead containers (Figure 2). The radiation leaving the source in every direction has to go through the lead shielding of the container thus the intensity is reduced according to the wall thickness of the container.

The wall thickness is the most essential parameter because it needs to be used for the calculation of the dose rate (1). The thickness can be measured directly only by opening the container, which can cause unnecessary exposure to the conducting officer. On the other hand, it can be calculated solving the following (2) equation using parameters, which can be measured outside of the container without any radiation exposure risk:

$$0 = -2x^3 + (4r + m)x^2 - (2r^2 + 2mr)x + mr^2 - (V_t - V_s)/\pi \quad (2)$$

x: shield thickness

r: radius of the container

m: height of the container

V_t: total cylinder volume of the full container calculated from the outer dimension

$$V_t = m\pi r^2 \quad (3)$$

V_s: solid cylinder volume of a solid lead container calculated from the weight of the container

$$V_s = \frac{s}{\rho} \quad (4)$$

s: the weight of the container

ρ: density in case of lead: 11.4 kg/dm³

The total cylinder volume (3) and the solid cylinder volume (4) can be calculated from the transportation documents and/or from measured parameters made by standalone instruments like a scale or measuring tape. If the measured and stated data are not in the same range, further inspection is needed. The deviation between the two volumes can be explained by the different material of the container (non-lead) or there can be some other goods (e.g. illegal drugs) placed next to the source.

Advanced Inspection Method

The next level of the inspection method requires the integration of several measuring instruments. I call this method advanced inspection, this leaves out all parameters stated in the documentation and rely only on the actual measured data.

Currently, I tested this inspection method only with a cylindrical isotope container and with one source per container, without the effects of other nearby radioactive packages.

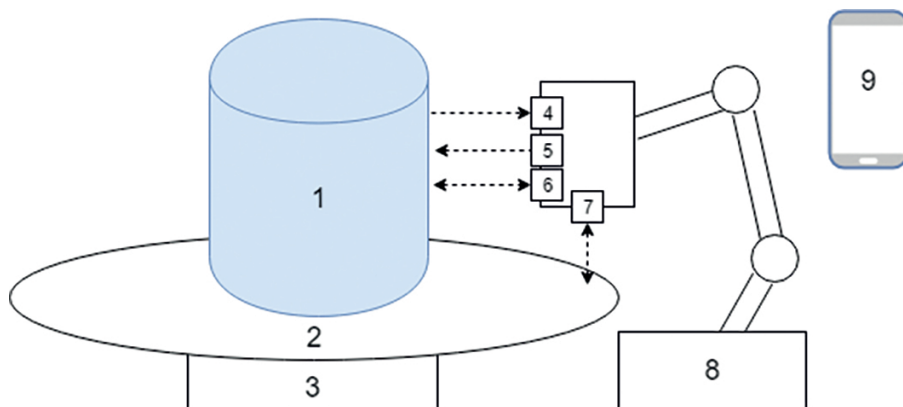


Figure 3. Schematic of an advanced radioactive package inspector system

Source: Made by the author

The container was placed on an automatically rotating platform (Figure 3 part 2). The platform has a built-in scale (Figure 3 part 3) to measure the weight of the container. A robotic arm (Figure 3 part 8) was installed next to the rotating platform, which is able to move the sensors automatically next to the surface of the container. In this application, the robotic arm was used for two reasons. Firstly, the radiation level next to a container can be high, thus human exposure can be avoided. Secondly, the container should be measured around at the same distance and with constant speed. Holding the dose rate meter by hand will add errors to the process, a robot does this task more accurately.

At the end of the robotic arm, a couple of sensor modules were installed. An ultrasonic distance sensor (Figure 3 part 7) is responsible for measuring the height of the container. The second distance sensor (Figure 3 part 6) controls the robotic arm to move the sensor head as close to the container as possible and after one turn it calculates the diameter of the container. A laser module (Figure 3 part 5) is also placed on the platform to see the actual point of interest

in the container. A dose rate meter (Figure 3 part 4) is used for registering the actual radiation level around the container. The detector should be calibrated according to the "IEC 61017:2016 Radiation protection instrumentation – Transportable, mobile or installed equipment to measure photon radiation for environmental monitoring standard" to reduce errors.⁸

After starting a measurement the instrument follows these steps: The robotic arm finds the nearest and lowest position to the container. The turntable starts rotating. After one round, the arm will lift the detectors head. The rotation and lifting process will continue until the top of the cylinder is reached. The whole surface of the container is scanned with this method. After analysing the data, the following information will be available:

- The highest dose rate at the surface of the container. It can create an alarm event if it is higher than the ADR limit.
- The shielding efficiency and consistency of the container. The main purpose of the container is to reduce the radiation coming from the source inside of the container. The radiation can escape in all directions. If the wall of the container is not homogeneous, or the source is not in the correct position, the radiation will be higher at one specific spot. This hot spot can be the consequence of an air bubble in the lead created during manufacturing or a fracture of the container as the result of an earlier accident. Every container which suffered damage should be excluded from any transportation.
- The diameter, height and the weight of the container. With all this information the thickness of the shielding wall can be estimated.
- The estimated activity of the source. The calculated activity can be compared with the activity stated in the shipment documentation and the category of the shipment.

Visualisation

If the container has a weak point in the shielding, the advanced inspection method will give only the highest dose rate as a result, but there will be no information about the location of this specific point. It is hard to give any point of reference to find the problematic part of the container. The best way is to visualise the whole container coloured according to the measured values. For this purpose, the dose rate was stored for every angular sector during the rotation. The saved values were combined with a cylindrical model to show the results in Figure 4.

⁸ International Standard 2016.

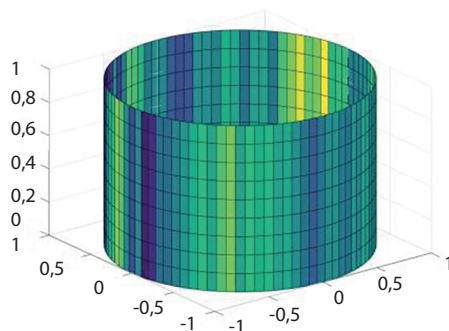


Figure 4. Visualisation of the radiation level of a container loaded with Cs-137

Source: Made by the author

The container in Figure 4 suffered no damage, but we can see that the shielding is inhomogeneous and/or the source is not placed in the centre of the container.

Isotope Identification

A potential error factor can be in the process of activity estimation. If the type of the isotope is not stated correctly in the documentation, the activity calculation will give the wrong result. To avoid this error the source in question should be identified. The identification can be conducted without opening the container. For this purpose, I used the SFK search and isotope identification unit (Figure 5). If the identification is not successful, the identified energy peaks and the count number at these peaks will give the energy level and probability of the gamma radiation, which can be used for the calculation as well.



Figure 5. SFK search and isotope identification unit

Source: Gamma Zrt. 2019

Surface Contamination of the Package

There is one additional factor that can cause a calculation problem. If the surface of the container is contaminated with radioactive material, the calculation can give a wrong activity estimation. Every surface contaminated container should be excluded from transportation. A traditional surface contamination monitor cannot be used in this case, because the effect of the source inside the container will modify the measured value. The best way is to take a smears sample from the surface of the container and check it far from the container in a low background measuring place with beta and gamma measuring unit. I used the IH-111L mobile spectrometric instrument for this application (Figure 6).



Figure 6. IH-111L Portable radiological measuring instrument

Source: Gamma Zrt. 2019

Validation of the Inspection Method

The validation of the inspection method was conducted by using real radioactive test sources in laboratory conditions. A 93.14 MBq activity Cs-137 source was placed in a lead container. The dimension and weight of the container were measured: height: 20.5 cm, diameter: 10 cm, weight: 16.7 kg. Wall thickness was calculated from these parameters: 3.23 cm.

The wall thickness of the container was measured with calipers. The result of this measurement was 3.45 cm wall thickness. The calculated and measured wall thickness already has a difference of 0.22 cm. This difference can be explained by the uneven wall thickness of the container.

The measured average dose rate at a distance of 30 cm from the instrument was 3.1 uSv/h. The calculated activity was: 198 MBq, which is 104.8 MBq more than the activity inside of the container. There are multiple causes of the difference. First, I used the average dose rate, secondly, I used standard lead parameters (build up factors). The container consists not only of lead but steel as well. If the radionuclide type is not correct i.e. instead of Cs-137 the calculation used Co-60, the result will be 2.6 MBq, and this major error shows the importance of isotope identification.

Conclusions

I analysed different levels of inspection methods. The basic level does not need any special tools or equipment. The advanced inspection method relies only on measured parameters, and not trusting the transportation documents. The models work in laboratory conditions but at a high error rate. In order to achieve more accuracy, the model should be modified. More tests should be conducted at different distances with different isotopes (Cs-137 and Co-60 etc.) and with different containers (lead, tungsten, steel, etc.), the algorithm should be able to handle more container types (e.g. rectangular). The advanced inspection method can be improved with multiple collimated radiation detectors. This will speed up the inspection time, and with collimation, the source localisation process can be more accurate. The instruments can be a useful tool to prevent a major industrial accident.⁹

The integration of spectrometric detectors to the system could give more information, and it can be used in other applications, like waste measurements.¹⁰

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⁹ KÁTAI-URBÁN 2017; KÁTAI-URBÁN et al. 2016.

¹⁰ PÁTZAY et al. 2017.