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THE EFFECT OF METALLIC MATERIALS ON THE FILTERING OF THE SPECTRUM OF MOBILE X-RAY GENERATORS WITH REGARD TO THE POSSIBLE INITIATION OF IMPROVISED EXPLOSIVE DEVICES

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Abstract. *This work deals with the study of changes in the spectrum of X-ray radiation produced by mobile generators, when passing through various metallic filters. The main goal is to provide an overview of the effect of these materials on the radiation spectrum, which is crucial for applications in the field of IEDs (Improvised Explosive Devices) detection and other security measures. The results will be used serve as study material for students dealing with this issue addressing this topic. In the detection of suspicious objects or IEDs, X-ray systems play a key role. In practice, however, IEDs can also be found equipped with sensors that react to X-ray radiation, and single pulse is often enough to initiate an unwanted detonation of an explosive device. For this reason, filters made of various metals are used in portable X-ray systems, which reduce the probability of activation of the IEDs sensor. The filters are installed directly in front of the X-ray generator. The aim of our work was to determine the effect of filtration with various materials on the spectrum and to determine the extent of this effect on the function of IEDs switches. There is an urgent need to determine what number of photons for specific energies is safe for X-ray sensitive sensors that could be used in IEDs. It is therefore necessary to conduct a professional study that would allow to investigate the issue more thoroughly based on scientific data. Using High-Purity Germanium (HPGe) gamma spectrometer GC2018 (CANBERRA), we measured the X-ray spectra of continuous portable X-ray source ECO 200DS, transmitted through filters made of Al, Ti, Brass, Cu, Zr, Pb, and W of different thicknesses. The results show that heavier and thicker filters effectively reduce low-energy X-rays, thereby "hardening" the spectrum and lowering total radiation intensity. Lead and tungsten filters were found to be most effective in preventing the triggering of X-ray sensitive sensors commonly used in improvised explosive devices (IEDs), although at the cost of reduced image resolution. The best results with regard to the quality of the captured image were achieved by using a 2 mm thick Cu filter, or a 0.5 mm thick Pb filter at a source-detector distance of approximately 2 m. Below the mentioned filter thicknesses, some sensors were already triggered occasionally.*

Keywords: *Improvised explosive device, X-ray, X-ray tube, X-ray imaging, X-ray sensitive sensor, X-ray spectroscopy, gamma spectrometry, High-purity germanium, Collimator, Characteristic radiation, Bremsstrahlung*

1. INTRODUCTION TO PROBLEMATICS X-RAY-RESPONSIVE IEDS

This work deals with the study of changes in the spectrum of X-ray radiation produced by mobile generators, when passing through various metallic filters. The main goal is to provide an overview of the effect of these materials on the radiation spectrum, which is crucial for applications in the field of IEDs (Improvised Explosive Devices) detection and other security measures.

In the detection of suspicious objects or IEDs, X-ray systems play a key role. In practice, however, IEDs can also be found equipped with sensors that react to X-ray radiation, and single pulse is often enough to initiate an unwanted detonation of an explosive device. For this reason, filters made of various metals are used in portable X-ray systems, which reduce the probability of activation of the IEDs sensor. The filters are installed directly in front of the X-ray generator. The aim of our work was to determine the effect of filtration with various materials on the spectrum and to determine the extent of this effect on the function of IEDs switches.

There is an urgent need to determine what number of photons for specific energies is safe for X-ray sensitive sensors that could be used in IEDs. It is therefore necessary to conduct a professional study that would allow to investigate the issue more thoroughly based on scientific data.

In the context of IEDs (Improvised Explosive Devices), sensors that react to X-rays can be encountered (see Fig. 1), where a single pulse is often sufficient to trigger an unwanted detonation. For this reason, portable X-ray systems use filters made of different metals to prevent the IEDs sensor from triggering.

There are 2 basic types of filters for portable X-ray systems:

1. Filters preventing activation of the radiation detection sensor – see Fig. 2,
2. Filters used to create an image with dual energy resolution.

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The first type of filters is used in portable X-ray systems to prevent the triggering of improvised explosive devices (IEDs) capable of detecting X-ray radiation directly in their circuit. Filters can reduce the number of photons from a portable X-ray machine and prevent the triggering of a sensor that responds to this type of radiation (the so-called anti-X-ray sensor – see Fig. 1) [1], [2], [3].

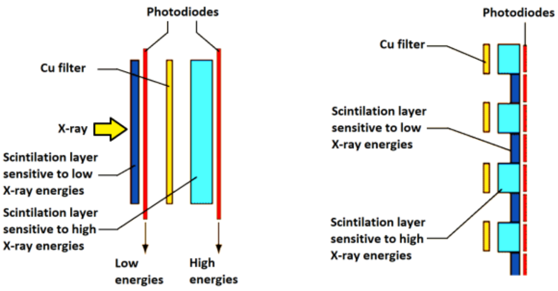

Figure 1. Example of two different designs of IEDs anti-X-ray switches [1]

Figure 2. Example of using a portable X-ray system to detect IED inside luggage

The second type of filters is used for imaging with resolution of the average atomic number of an X-rayed material. This is the standard X-ray imaging mode for safety X-rays. It tells the operator based on color whether the object is organic, inorganic, metallic etc. – see Fig. 3. To obtain such an image, high- and low-energy X-ray imaging is required. The software performs 2 scans – the first without a filter in front of the beam and the second with a filter (this is called pseudo-dual energy).

Figure 3. Dual energy beam imaging

2. Effect of filtration on X-ray spectrum

Since the probability of X-ray interaction, described by the linear attenuation coefficient (μ), increases sharply as radiation energy decreases (because higher-energy photons are more penetrating) and also increases with the atomic number (Z) of the filter material (heavier elements provide better shielding), the filter primarily absorbs the low-energy portion of the spectrum while allowing most of the high-energy photons to pass through.

In general, after filtration, the spectrum of the transmitted radiation is harder, i.e. only the more penetrating components of the radiation pass through, at the same time the total intensity of the radiation decreases, because part of it has been absorbed by the filter. Of course, either change can affect the IED sensors.

The Fig. 4 shows the changes in the relative intensity of X-rays generated by a tungsten X-ray tube operating at 100 kV for three different filter thicknesses:

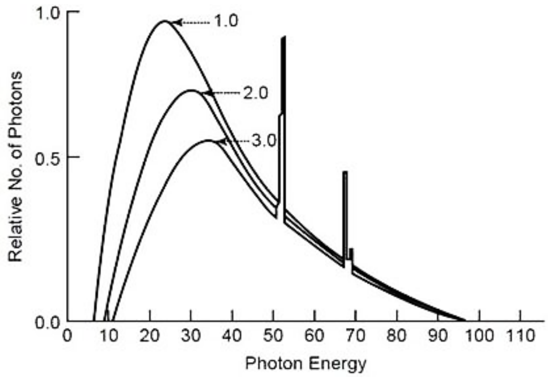

Figure 4. Illustrative example of the influence of different filter thicknesses on the shape of the X-ray Spectrum [4]

3. Experimental equipment used

3.1. Technical parameters of the X-ray sources used

Tested X-ray generator was a mobile handheld continual X-Ray source ECO 200DS of the manufacturer COMET, with fixed tungsten anode and adjustable anode voltage of 30 – 200 kV (see Fig. 5) [5].

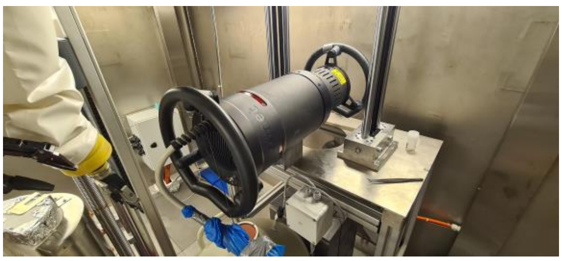

Figure 5. Mobile X-Ray source ECO 200DS with fixed tungsten anode and nominal anode voltage of 200 kV

Device parameters:

- Maximum voltage: 200 kV
- Maximum current: 6 mA
- Focal spot size: 1 mm

• Laser aiming system.

In addition to the ECO 200DS, the XRS-3 pulsed X-ray source (operating voltage: 270 kV) (see Fig. 6) [6] was intended to be used in the study; however, the high dead time of the detector, even at maximum beam collimation (aperture diameter = 1 mm), rendered its use unsuccessful.

Figure 6. Mobile battery-powered power supply XRS-3 with fixed tungsten anode, with a nominal anode voltage of 270 kV

3.2. Technical parameters of the spectrometer used

Spectral measurements of the X-ray source were performed with a High-Purity Germanium (HPGe) detector GC2018 from CANBERRA, cooled by liquid nitrogen, providing high-resolution gamma spectroscopy data. The detector together with the preamplifier, amplifier, control unit and advanced control software GENIE-2000, equipped with an extensive library of spectra of known radionuclides, forms a top system for gamma spectroscopy. the GC2018 is a coaxial p-type HPGe detector with notably decreasing efficiency for X- and gamma rays in the energy les then 60 keV.

To characterize highly active samples, the HPGe detector is shielded using a modular tungsten

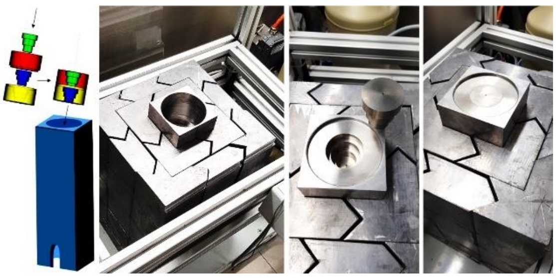

Figure 7. Lead shielding of HPGe detector with inserted modular tungsten collimator

collimator with a 1 mm, 2 mm, or 3 mm diameter aperture, supplied by Czech manufacturer INKOSAS. This collimator is inserted into a specially designed lead insert that surrounds the detector, manufactured by the Research Centre Řež (Fig. 7). A 100 mm thick shielding built of lead bricks was also laid around this insert (Fig. 7).

3.3. Parameters of the filters used

The following filters were selected for the measurements:

- Aluminium: thickness 2 mm
- Titanium: thickness 2 mm
- Brass: thickness 2 mm
- Copper: thickness 1 mm, 2 mm, 3 mm, 4 mm
- Lead: thickness 0.5 mm, 1 mm, 1.5 mm, 2 mm
- Zirconium: thickness 1 mm, 2 mm
- Tungsten: thickness 3.6 mm and 4.4 mm

The tungsten filter was made by 3D prinsting – see e.g. [7]

The basic criterion for selecting filters was the atomic number in order to obtain a scale – see Table 1. Most of the listed filters (except brass and zirconium) are supplied as standard accessories of the tested commercially produced X-Ray sources.

Table 1. Physical characteristics of the filters used, having a direct impact on the ability to absorb ionizing photon radiation

Material	Atomic number Z	Relative atomic mass	Density (kg/m^3)
Al	13	26.982	2 700
Ti	22	47.867	4 506
Brass	-	-	8 500
Cu	29	63.546	8 940
Zr	40	91.222	6 520
W	74	183.840	19 250
Pb	82	207.200	11 340

4. Experimental part

The aim of the experiment was to determine the effect of filtration by different materials on the spectrum of bremsstrahlung and to determine the degree of this effect on the function of IEDs switches.

Testing of the XRS-3 pulsed source (Fig. 6) was unsuccessful, as it was not possible to reduce the detector dead time to an acceptable level even with the maximum possible shielding of the detector by a tungsten collimator with an aperture of 1 mm. The reason is the pulsed nature of the source. At the used source-detector distance of 600 mm, the dose in the pulse was still up to 10 μGy, which, given the pulse width of only 50 ns, corresponds to a dose rate of 200 Gy/s, or 720 kGy/h, that our device (designed primarily for the characterization of weak radioactive samples in units of μGy/h) could not cope with.

The experimental use of XRS-3 demonstrates the importance of choosing an X-ray equipment. For gamma spectrometric analysis on a selected type of device, pulsed sources can be excluded.

All measurements of X-ray spectra, described in sections 4.1. and 4.2., were therefore carried out with a continuous source ECO 200DS, through a tungsten collimator with an aperture of 2 mm diameter, at a focus-detector distance of 690 mm, at an anode voltage of 200 kV and a current of 1 mA. Each measurement lasted 300 s. The obtained spectra were subsequently corrected for the energy efficiency of the detector.

4.1. First measurement

An absolute comparison was obtained for Open field, 2 mm Al, 2 mm Ti, 2 mm Brass, 2 mm Cu, 2 mm Zr, and 2 mm Pb – see Fig. 8. The resulting spectra made good physical sense with regard to the atomic numbers Z, the density and thicknesses of the various filters used, which fundamentally affect the shape of the spectra and their shifts in the energy and intensity scale.

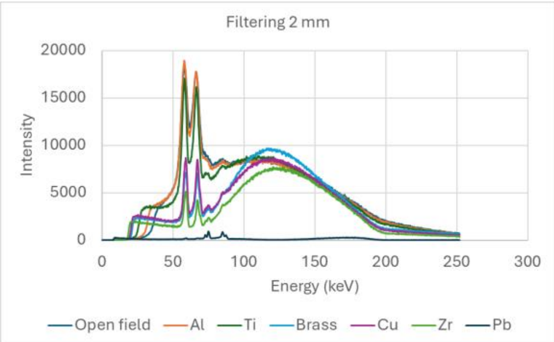

Figure 8: X-ray spectra of ECO 200DS for different filters of the same thickness

In addition to bremsstrahlung, the spectra also show K-lines of characteristic tungsten radiation ($K_{\alpha 1}$: 59.32 keV, $K_{\alpha 2}$: 57.98 keV, $K_{\beta 1}$: 67.24 keV), originating mostly from the tungsten anode of the X-ray tube, and to a lesser extent from the tungsten collimator. Furthermore, characteristic lead lines ($K_{\alpha 1}$: 74.97 keV, $K_{\alpha 2}$: 72.80 keV, $K_{\beta 1}$: 84.94 keV) originating from the lead shielding of the detector, and in the case of using a Pb filter, primarily from this filter are clearly visible.

The effect of filtration in X-rays spectrum is also referred under a large database named as X-ray mass attenuation coefficients accessible through NIST website. [8]

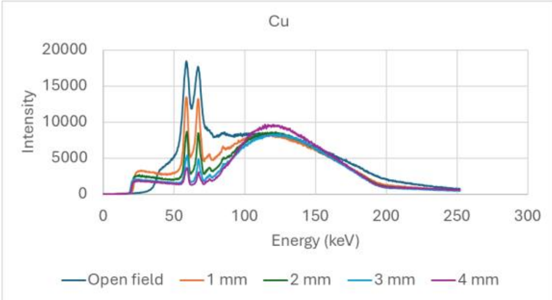

Figure 9: X-ray spectra of ECO 200DS for copper filters of different thicknesses

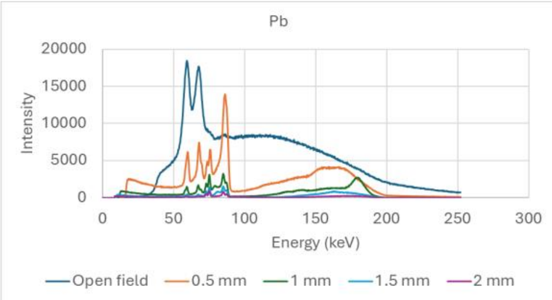

Figure 10: X-ray spectra of ECO 200DS for lead filters of different thicknesses

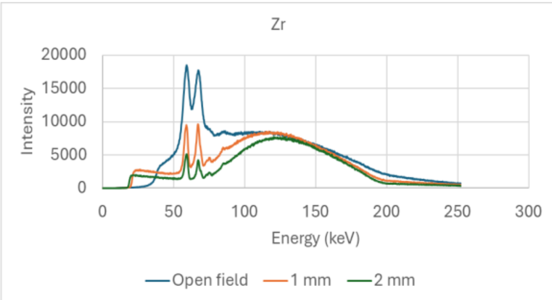

Figure 11: X-ray spectra of ECO 200DS for zirconium filters of different thicknesses

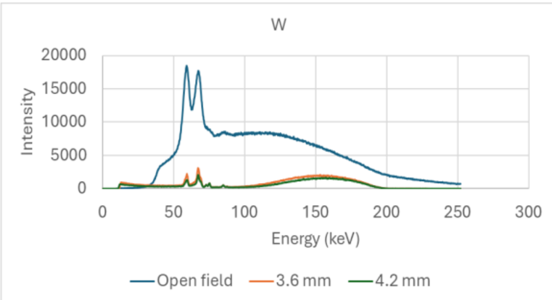

Figure 12: X-ray spectra of ECO 200DS for tungsten filters of different thicknesses

The database is merging the attenuation coefficient for all materials from Hydrogen to Uranium for X-rays from 1 keV to 20 MeV. [9]

In recent years it has also been simulated through different Monte-Carlo codes [10].

4.2. Second measurement

The second experiment focused on the effect of different thicknesses of filters made of the same material.

In this case, the filter materials tested were copper with a thickness of 1 mm, 2 mm, 3 mm, 4 mm and 5 mm, as well as lead with a thickness of 0.5 mm, 1 mm, 1.5 mm and 2 mm. The resulting X-ray spectra are shown in Fig. 9 and 10. It was also interesting to compare the effect of 1 mm and 2 mm Zr filters (see Fig. 11), as well as 3.6 mm and 4.4 mm tungsten (W) filters (see Fig. 12).

The filters were evaluated for their effectiveness in preventing the triggering of IED detection sensors. The image quality after filtering depends also on the distance of the X-ray source from the scanned object.

4.3. Testing with real X-ray sensitive sensors

The experimental setup is schematically shown in Fig. 2 at a source-detector distace of 2 m. Lead and tungsten filters proved to be the most effective in reducing detectable radiation intensity. While denser filters allow fewer photons to reach the anti-X-ray sensor, they also reduce the number of X-rays reaching the detector's flat panel, leading to a significant decrease in image signal to noise ratio (SNR).

The best results with regard to the quality of the captured image were achieved by using a 2 mm thick Cu filter or a 0.5 mm thick Pb filter – see Fig. 13. Below the mentioned filter thicknesses, some sensors were occasionally triggered.

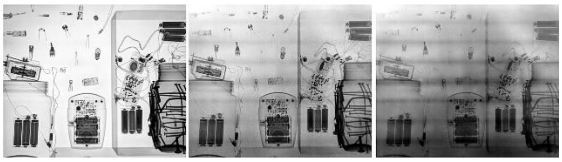

Figure 13. Image quality at (from left): open field, 2 mm Cu, 0.5 mm Pb

5. Conclusion

The use of metallic filters significantly affects the X-ray spectrum. Knowledge of these effects is crucial for applications in the field of detection of suspicious objects or IEDs and the improvement of imaging technologies.

The measurements confirmed the theoretical assumption that the atomic number Z, density and thickness of the used filters fundamentally affect the shape of the resulting spectra and their shift in the energy and intensity scales.

The filters were tested for their ability to prevent the triggering of X-ray sensitive sensors. The measurements showed that lead and tungsten filters were most effective for reducing detectable radiation intensity, but at the same time they significantly reduce the signal-to-noise ratio (SNR) in the resulting image. The best results with regard to the quality of the captured image were achieved by using a 2 mm thick Cu filter, or a 0.5 mm thick Pb filter at a source-detector distance of approximatelly 2 m. Below the mentioned filter thicknesses, some sensors were already triggered occasionaly.

Recommendations for further research include a more detailed analysis of the effect of different filter thicknesses or combination of diferent materials, as well as different source-detector distances, to optimize the results. The results could be valuable for students and experts involved in X-ray spectroscopy and security technologies.

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References

1. J. Howell, "Filters for Portable X-rays: What do they actually do?", Linkedin, 2020
2. Teledine ICM, "PIR Sensors in IEDs using constant potential generators", Counter-IED Report, 2023 https://counteriedreport.com/wp-content/uploads/2023/05/63-67-Teledyne-ICM-article-Counter-IED-Report-Spring-Summer-2023.pdf
3. International Bomb Disposal and Counter IED Professionals, "Passive Infrared Sensors (PIR) vs Fixed and Adjustable Kv portable X-Ray Generators", Linkedin, 2021
4. D. Zoul, M. Zelený, "Vliv metalických materiálů na filtraci spektra brzdného záření pulzních generátorů s ohledem na možnou iniciaci nástražných výbušných systémů (The influence of metallic materials on the filtering of the bremsstrahlung spectrum of pulse generators with regard to the possible initiation of improvised explosive devices)", Jaderná energie (Nuclear energy), 2/2024, pp. 30-37
5. https://issuu.com/comet-xray/docs/comet_portables_and_mobile_catalog_v5
6. https://www.elp-gmbh.com/en/produkte/golden-engineering-xrs3-gen-4/
7. X. Ma, M. Buschmamm, E. Unger, P. Homolka, "Classification of X-Ray Attenuation Properties of Additive Manufacturing and 3D Printing Materials Using Computed Tomography From 70 to 140 kVp", *Front. Bioeng. Biotechnol.*, vol. 9, 2021. https://doi.org/10.3389/fbioe.2021.763960
8. https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients
9. https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html
10. R. Taleei, M. Shahriari, "Monte Carlo simulation of X-ray spectra and evaluation of filter effect using MCNP4C and FLUKA code", *Appl. Radiat. Isot.*, vol. 67, no. 2, pp. 266-271, 2009. https://doi.org/10.1016/j.apradiso.2008.10.007