Tracking of fissile material by means of coincident neutron detection - Fission Meter vs. Slab Counter

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Abstract:

In the context of fissile material detection, discrimination between changes of the natural neutron background, industrial material, and a real neutron source, indicating the presence of nuclear material, is tremendously important. The negligence of such material may lead to drastic if not fatal consequences to the general public in case the material in question is used in explosive devices such as Improvised Nuclear Devices (IND). To achieve the discrimination required, measurements of coincident neutrons are feasible because only fissile material emits coincident neutrons. Two neutron detection systems, the Fission Meter by Ametek/Ortec and the Slab Counter by Canberra, were tested concerning their quality of detecting nuclear material as mentioned above, using primarily a variety of Plutonium sources with different isotopic compositions provided by the Institute of Transuranium Elements (ITU) of the Joint Research Centre at Ispra, Italy, where the measurements were performed. We also examined the influence of shielding effects of the materials which would possibly be part of an IND. The results of these measurements and an assessment of the reliability of the two detection systems concerning fissile material verification will be presented.

Keywords: neutron measurements, coincident neutrons, fissile material detection

1. Introduction

The current threat of the use of nuclear material during terrorist attacks, e.g. by means of improvised nuclear devices, is a widely discussed matter nowadays. Such devices may have severe consequences to the general public. In any such case it is vital to investigate which type of nuclear material could be involved, therefore sophisticated measurement techniques are required. Whereas gamma measuring devices are more commonly used, the utilization of neutron measurement techniques may be very valuable in some cases as the nuclear device could be surrounded by shielding material which gamma radiation cannot pass. Neutrons, on the other hand, may still be detectable. Additionally, the neutron background is usually low.

The neutron measuring component of common hand-held radiation measuring devices is not very suitable for such measurements because its detection volume is generally too small. Large volume neutron detection devices are required to distinguish between nuclear and industrial material by means of detecting the presence of coincident neutrons.

2. Neutron detection systems

Two neutron detection systems suitable for measurements of coincident neutrons were compared to verify their ability to reveal the presence of nuclear material. These systems are the Fission Meter by Ametek/ORTEC and the Slab Counter by Canberra. Both systems are equipped with ^{3}He-tubes for neutron detection and polyethylene coating for moderation of fission neutrons as ^{3}He is best suited for detecting neutrons in the thermal energy range. The most important physical parameters of the devices are listed in table 1. Their most significant difference in appearance is the fact that the Fission Meter comprises two panels connected by hinges which allows for flexible arrays of the panels with different angles relative to each other (see figure 1 on the left). The Slab Counter, respectively, only consists of a single panel (see figure 1 on the right). Various Slab Counters can be positioned around a source to match different geometries and to achieve an optimal efficiency. For the comparison in this experiment, two Slab Counters were used in order to match the measuring options with the Fission Meter.

Type	Fission Meter	Slab Counter
Manufacturer	Ametek/ORTEC	Canberra
Gas characteristics	^{3}He ($7.6 \cdot 10^5$ Pa)	^{3}He ($4.2 \cdot 10^5$ Pa, $5 \cdot 10^4$ g/cm^3)
Diameter per tube	2.54 cm	2.54 cm
Length per tube	48.26 cm	33 cm
Number of tubes	15 per panel => 30 per device	6 tubes per counter
Active area	~1800 cm^2 (15 tubes, 0° geometry)	~500 cm^2
Moderator	Polyethylene, on one side (minimum 2.54 cm)	Polyethylene, enclosing the tubes (minimum 1.7 cm)
Weight	26 kg	11.5 kg

Table 1: Comparison of physical parameters of neutron detection systems.

The Fission Meter system can be operated in three different modes [1]:

- Mobile search mode
- Static search mode
- Characterization data collect mode

In the mobile search mode temporal changes of the neutron count rate are displayed. This mode is therefore not suitable for static measurement set-ups as described in this paper. In the static search mode, discrimination between the total count rate and the non-cosmic count rate is shown. The cosmic part of the count rate refers to non-correlated neutrons caused either by the natural neutron background which creates a yield when entering the detection volume or industrial material emitting non-coincident neutrons. The non-cosmic part consists of neutrons emitted by sources generating coincident neutrons by spontaneous fission. So measurements performed in this mode give a hint if the count rate values are created by fissile material, industrial material, or just the natural background.

Based on the measured count rate data, the Fission Meter generates multiplicity plots in the characterization data collect mode, displaying the distribution of the counts over the multiplicity numbers. In case these plots show a Poisson distribution, only randomly emitted neutrons are present. A distribution of a neutron source representing industrial material should be similar to one caused by the natural background. In contrast, fissile material such as Plutonium emits coincident neutrons, so the distribution of the multiplicity numbers does not equal that of a purely random emission. Thus, by detecting coincident neutrons, the detection systems can verify the presence of fissile material. For further details see, e.g., [2].

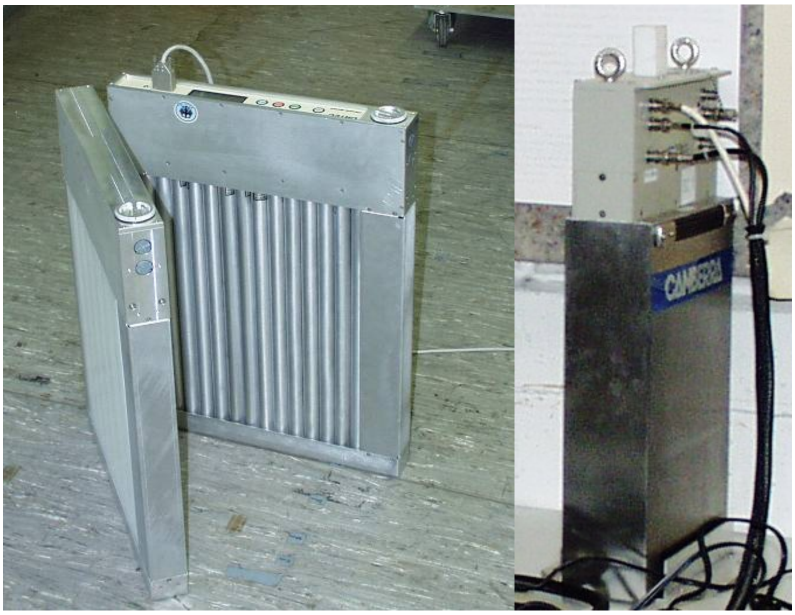

Figure 1: Detection panels of the Fission Meter (left) and the Slab Counter (right).

The Slab Counters are also capable of measuring coincident neutrons by means of multiplicities. They measure the Singles, Doubles and Triples rates as defined by Ensslin et al [3]. From these rates it is possible to determine the fissionable mass, multiplication and alpha if the efficiency of the detector set-up is known. The efficiency in general is not known precisely for a mobile set-up intended for the in-situ measurement of unknown radioactive material as described here. The efficiency of various Slab Counter set-ups with 4, 6 and 8 slab counters had been measured with different ^{252}Cf sources at Fraunhofer-INT previously [4]. For the measurements here where only two slab counters were used two ^{252}Cf sources of the ISPRA facility were used for efficiency calibration.

The efficiency can be determined from the Singles rates of the ^{252}Cf sources assuming that the alpha value is 0 and the multiplication is 1.

3. Measurement set-up

The measurements were carried out at the Institute for Transuranium Elements (ITU) at the Joint Research Center (JRC) in Ispra, Italy. The ITU provided lab space and, most importantly, the neutron sources used for this study. The neutron measurement devices belong to the Fraunhofer-INT.

The arrangement of the detectors or its panels affects, among other factors, their efficiency. According to previous measurement results, the Fission Meter's maximum efficiency is achieved when the panels are placed at a relative angle of 45° to each other with the moderation material on the outside, the source being wedged between the panels (see figure 2). If the source is placed in the center of the geometry the corresponding efficiency value is approximately 6 % [5]. In the set-up used here the source was placed outside the center of the geometry at 24 cm distance to the center of the panels. The efficiency determined by the measurement of the two ^{252}Cf sources was 1.42 +/- 0.045 %. With the Slab Counters, several geometries were tested. The measurements were performed with the two devices facing each other with the source placed in between (see figure 2). The distance between the front faces of the panels was 23 cm and the corresponding efficiency was determined as 4.85 +/- 0.11 %. It was tried to position the sources in the vertical and horizontal middle position of the active detector surface as good as possible.

Figure 2: Measurement set-up of the Fission Meter (left) and of the Slab Counters (right).The distance of the source on the tripod to the center of one of the Fission Meter pannels was 24 cm. The distance between the front surfaces of the Slabs was 23 cm

Figure 3 shows the electronic components and laptops for the two systems. The Fission Meter's data taking device is a ruggedized pocket PC connected by a serial cable. The Slab Counters are controlled by a JSR14 which comprises the high voltage unit and a shift register.

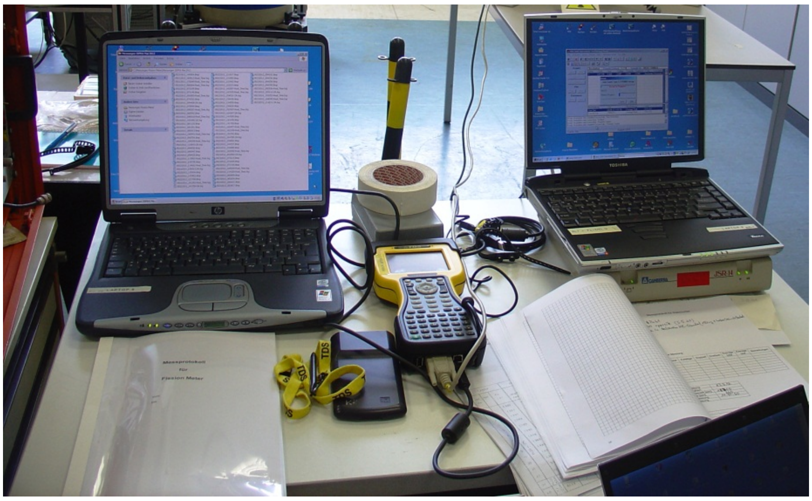

Figure 3: The Fission Meter data collection device (in the center of the picture), the Slab Counter high voltage supply and data collection unit (right, beneath the notebook) and notebooks.

In order to test the systems' ability to detect nuclear material by coincident neutrons, two ^{252}Cf sources were used for calibration measurements. As nuclear material several Pu sources with different isotopic compositions, ranging from Reactor Grade Pu (RG Pu) to Weapons Grade Pu (WG Pu) were used. The Plutonium masses and isotopic compositions of these sources are listed in table 2. In addition to the Pu sources two MOX sources were measured, but only with the Slab Counters for logistic reasons.

Measurements were also performed with additional shielding which consisted of a 1.5 cm thick layer of explosives simulat around the source.

Source	Mass Pu [g]	Pu-239 Content [At.%]	Pu-240 Content [At.%]
Pu CBNM 61	6.626	62.7	25.4
Pu CBNM 70	6.665	73.4	18.2
Pu CBNM 84	6.690	84.4	14.2
Pu CBNM 93	6.625	93.4	6.3
PuO2 No. 1-10	1.98-2.0	85.2	13.2
PuO2 No. 20a	4.98	85.2	13.2
PuO2 No. 21a	9.97	85.2	13.2
PuO2 No. 22a	19.92	85.2	13.2
PuO2 No. 30	20.57	69.3	26.3
Pu Metal No. 40	8.45	89.0	10.2
MOX ENEA-01	1093	66.3	28.1
MOX ENEA-02	1093	66.4	28.4

Table 2: Overview of neutron sources investigated in this survey.

4. Measurement results

In the table 3 the total count rate and the non-cosmic count rate of the Fission Meter measurements for all sources is listed. We performed measurements in both the static and the characterization mode. If the time did not allow us to use both modes, we concentrated on the latter mode as it provides a more valuable output. In these cases, the non-cosmic part of the count rates could not be listed in table 3.

The count rate values of Californium and Plutonium sources measured with the Fission Meter were all significantly above the background value (see table 3) and were created almost completely of non-cosmic neutrons, indicating the presence of fissile material clearly. The addition of shielding material generally led to an increase of the count rate values which shows that the moderation material of the detection unit of the device alone is insufficient for thermalizing the incoming neutrons. Unfortunately, the background value of the count rate also comprises a non-cosmic part which could not be prevented.

Source and Geometry	Count Rate [cps] Total (N-Cosmic)
None (Background)	5.2 (4.6)
Cf-252 6001 NC, no shielding	1758.5 (1758.5)
Cf-252 542 H9-716, no shielding	4405.9 (3701)
PuO2 (0.2 g) with 13 % Pu-240 No. 10, no shielding	14
PuO2 (0.2 g) with 13 % Pu-240 No. 2, no shielding	13
Pu CBNM 61, no shielding	60.32 (59.7)
Pu CBNM 61, explosive simulate shielding	77.76 (76.2)
Pu CBNM 70, no shielding	46.26 (44.9)
Pu CBNM 70, explosive simulate shielding	59.8 (59.8)
PuO2 (0.2 g) with 13 % Pu-240 No. 1a, 2, 3, 4a, 5, 6, 7a, 8, 9, 10, 20a, 21a, 22a, no shielding	171
Pu CBNM 93, no shielding	14.7 (14.3)
Pu CBNM 93, explosive simulate shielding	18.04 (18)
Pu Metal 8.4 g No. 40, no shielding	24.5 (24.5)
Pu Metal 8.4 g No. 40, explosive simulate shielding	29.2 (29.2)
Pu CBNM 84, no shielding	22.7 (22.7)
Pu CBNM 84, explosive simulate shielding	28.2 (27.9)
PuO2 (0.2 g) with 13 % Pu-240 No. 22a, no shielding	75
Pu PM1, PM2, PM3, 13 g + 2 x 19 g, no shielding	59

Table 3: Total count rates and non-cosmic count rate for all neutron sources measured with the Fission Meter

Figure 3 shows the comparison of two multiplicity plots created by the Fission Meter's characterization mode. The plot of the background measurement on the left differs from a purely random Poisson distribution. This may have occurred because of influences of shielded neutron sources, being in storage in the vicinity. However, the multiplicity numbers of the distribution are low. In contrast, a Pu source (figure 3 on the right) shows higher multiplicity numbers and larger differences between the measured data and the Poisson distribution. This demonstrates that fissile material was indeed detected here.

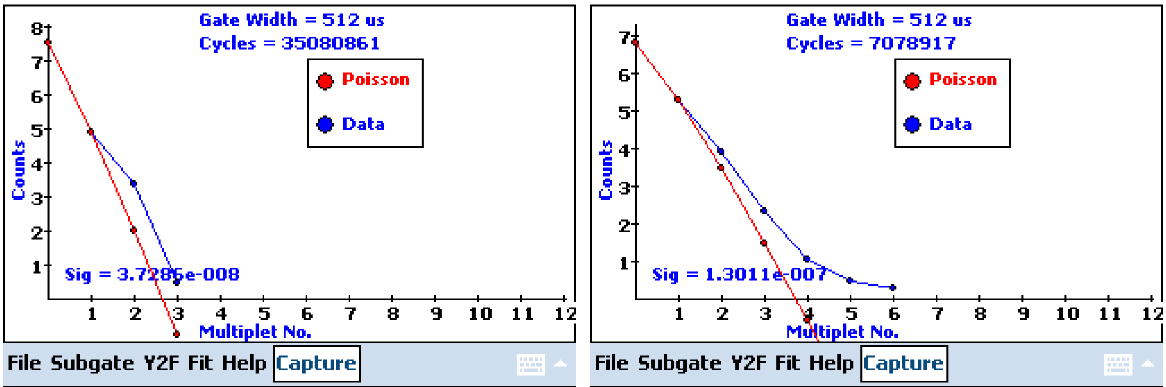

Figure 3: Multiplicity plots of the Fission Meter for a background measurement (left) and with the source Pu CBNM 61 (right).

Table 4 shows the count rates for the different sources measured with the Slab Counters. In general the rates for the samples with shielding are higher than the rates without shielding. This is true for both measurement systems and is caused by the moderator thickness which is too low for optimal moderation of fission neutrons. Thus additional moderator material, which the explosives simulate used as shielding represents, enhances the count rate.

Source and Geometry	S [cps]	ΔS [cps]	D [cps]	ΔS [cps]	T [cps]	ΔS [cps]
None (Background)	1.2	0.06	0	0	0	0
Cf-252 6001 NC, no shielding	5955.69	3.16	292.77	2.53	7.66	1.48
Cf-252 542 H9-716, no shielding	15254.94	5.08	752.58	5.96	22.94	5.34
PuO2 (0.2 g) with 13 % Pu-240 No. 10, no shielding	22.65	0.11	0.37	0.02	0.01	0
Pu CBNM 61, no shielding	198.32	0.23	3.22	0.05	0.07	0.01
Pu CBNM 61, explosive simulate shielding	215.68	0.16	3.67	0.03	0.09	0.01
Pu CBNM 70, no shielding	146.68	0.2	2.23	0.04	0.04	0.01
Pu CBNM 70, explosive simulate shielding	159.33	0.21	2.54	0.04	0.05	0.01
Pu CBNM 93, no shielding	35.88	0.07	0.6	0.01	0.01	0
Pu CBNM 93, explosive simulate shielding	38.66	0.1	0.69	0.02	0.01	0
Pu No. 30, no shielding	478.42	0.4	8.72	0.11	0.18	0.02
Pu Metal 8.4 g No. 40, no shielding	45.01	0.03	1.26	0.01	0.02	0
Pu Metal 8.4 g No. 40, explosive simulate shielding	49.31	0.12	1.47	0.02	0.03	0
Pu CBNM 84, no shielding	69.3	0.14	1.39	0.02	0.02	0
Background PERLA	40.81	0.03	0	0	0	0
MOX ENEA-01 Perla	3630	1.01	54.69	0.64	1.14	0.26
MOX ENEA-02 Perla	4453.95	3.86	71.19	2.65	0.48	1.2

Table 4: Single count rate (S), Double count rate (D) and Triple count rate (T) for all neutron sources measured with the Slab Counters

Due to limited measurement time the needed statistical accuracy for the Triples rate could not always be reached. The uncertainty in the Triples rate is the main factor in the uncertainty of the ^{240}Pu effective mass. Table 5 shows the $^{240}Pu_{eff}$ values determined from the slab counter measurements.

Source	Mass Pu [g]	^{239}Pu Content [At.%]	^{240}Pu Content [At.%]	$^{240}Pu_{eff}$ mass declared [g]	measured [g]
Pu CBNM 61	6.626	62.7	25.4	2.34	2.02
Pu CBNM 70	6.665	73.4	18.2	1.59	1.45
Pu CBNM 84	6.690	84.4	14.2	0.999	1.06
Pu CBNM 93	6.625	93.4	6.3	0.423	0.34
PuO2 No. 30	20.57	69.3	26.3	5.96	5.23
Pu Metal No. 40	8.45	89.0	10.2	0.889	0.86
MOX ENEA-01	1093	66.3	28.1	53.77	31.7

Table 5: ^{240}Pu effective mass determined by the Slab Counter measurements compared to the value of the ^{240}Pu effective mass calculated from the source certificates

5. Conclusion

It could be shown that the Fission Meter and the Slab Counters are able to detect the presence of fissionable material if an unknown object containing radioactive material is discovered. Furthermore the slab counter measurements showed that with a simple efficiency calibration the effective ^{240}Pu mass can be estimated. This worked quite satisfactory for the available reference sources. For the Fission Meter the multiplicity distributions have to be evaluated visually on the screen of the pocket PC. Thereby fission sources can be discriminated from random neutron sources. The Fission Meter and the Slab counters are valuable devices for the determination of the presence of fissionable material in an object containing radioactive material and thus an important tool to prevent illicit trafficking of nuclear material.

6. Acknowledgements

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7. References

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