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A Fast Neutron and Gamma Ray System for the Detection of Illicit Materials Based on Simple Isotopic Sources

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Abstract

A simple Fast Neutron Gamma Ray system based on a common neutron and gamma sources, namely 252Cf and 137Cs, has been simulated using the MCNP4B Monte Carlo code. More than 160 materials from different categories were considered and the simulations showed that the examined facility offers remarkable benefit in discrimination between illicit and not illicit materials. The use of three beams, rather than two, further improves the material discriminator.

Keywords: FNGR Systems; MCNP4B; ^{252}Cf, ^{137}Cs, illicit materials

1. Introduction

Abandoned landmines and terrorist bomb attacks are severe issues threatening our society. To counter this threat, several technologies have been developed to detect explosive detection systems. The detection of hidden explosives is a major analytical problem that requires highly sensitive and specific methods for its solution. The existing technologies for explosive detection can be divided into three categories: non-explosive component detection, vapor and trace detection, and bulk detection. Unfortunately there isn't method without both benefits and drawbacks. For this reasons the improvement of security systems -not only in the aviation industry, is compulsory. In this respect, the scientific focus on the development of new illicit materials detection technologies is significant [1-2].

In the present day many inspection systems are based on the dual energy method with a view to scan hand baggage, parcels and containers. The discrimination of materials is achieved when the inspected object is alternately irradiated by X-ray with different energies. By comparing the difference in attenuation coefficients between organic and inorganic materials for high and low energy X-ray, the dual-energy method has been widely applied in luggage X-ray inspection systems for the purpose of material discrimination. With this method is easy to discriminate not only metals from organic materials, but also high-atomic number metals such as lead and uranium from common metals such as iron and aluminium. However are almost unfeasible to differentiate a wide range of organic materials [1-8].

The limitations of X-ray systems have motivated the development of alternative methods, including those based on neutrons. Fast neutrons are suitable to explore bulky objects because of their high penetration. An excellent scientific review by Buffler [3] classifies neutron-based methods in seven general categories. Useful information about the neutron and photon based techniques for chemical explosives detection in air cargo there are in the recently review by Runkle et al. [9]. Neutrons based systems and techniques are superior to X-ray systems but have not implemented by the security industry. We agree entirely with Buffer and Tickner [10] that the reasons for this are the high cost and the complexity of the neutron based systems.

The purpose of this work is to evaluate if a simple Fast neutron Gamma Ray (FNGR) system based on a small isotopic sources can offer significant information for the detection of illicit materials. Previous simulations by Fantidis and Nicolaou [11] have shown the benefit of using three instead of two nuclear beams in the same system. Also many dual, triple and quadruple systems have been evaluated at the same article. In this work a ^{252}Cf source and a ^{137}Cs gamma ray source, have been simulated using the MCNP4B Monte Carlo [12] code with intention to assess a new FNGR system.

2. Fast Neutron and Gamma Ray method

For the ideal case of narrow-beam geometry in which scattered radiation do not reach the detector, the transmission of the monoenergetic fast neutrons and gamma or X-rays through the object of density ρ and thickness x can be calculated by means of the following:

$$\frac{I_n}{I_n^0} = e^{-\mu_n \rho x} \quad (1)$$

and

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$$\frac{I_g}{I_g^0} = e^{-\mu_g \rho x} \quad (2)$$

for neutrons and gamma rays respectively. μ_n, μ_g are the neutron and gamma ray mass-attenuation coefficients correspondingly, I_n and I_g are the measured yield through at the investigated object and I_n^0, I_g^0 are the measured yield without the object. The logarithmic ratio R, of the neutron and gamma-ray attenuation coefficients is:

$$R = \frac{\mu_n}{\mu_g} = \frac{\ln \frac{I_n}{I_n^0}}{\ln \frac{I_g}{I_g^0}} \quad (3)$$

The ratio *R* describes the material of the unknown object and is independent of its thickness.

The precise calculation of R values is necessary with the aim to distinguish the unknown object. The absence of monoenergetics sources leads to beam-hardening effects. In accordance with Liu et al. [7] there is an uncertainty of 1% on I_n / I_n^0 value and 0.1% on I_g / I_g^0 value. Using these values is easy to find the minimum and the maximum R value for each material.

3 Facility and sources

The geometrical configuration of the facility used in the present work is schematically shown in Fig. 1 and is similar to the one described previously, in Ref. 11 and 13 by Fantidis and Nicolaou. A cylindrical steel collimator, with a length of 100 cm and diameter of 3 cm, collimates a neutron or a γ-ray beam towards the object. The intensity of the beam transmitted through the object is calculated at the rectangular detector cell with dimensions 1.5 × 1.5 × 5 cm^3. The cell is collimated by a steel cylindrical collimator having a length of 50 cm and a diameter of 1.5 cm. The unknown object is considered in a cubic form with a side of 20 cm and it is symmetrically placed around the axis of the two collimators at a distance of 200 cm and 150 cm from the source and the detector cell respectively. An isotropic disc source, with diameter of 3 cm, is considered in the simulations.

The ^{252}Cf neutron source is simulated like a Watt fission spectrum using the coefficients provided by the MCNP4B code. The source emits neutrons extends up to 10 MeV with a mean energy at 2.3 MeV. Further to the neutron emission, ^{252}Cf emits photons with a mean energy of 0.8 MeV [14]. ^{137}Cs (E_γ= 0.662 MeV) was considered as gamma ray source. Just for the comparison two X-rays sources with 4 and 9 MeV end point energies with Bremsstrahlung spectra were also simulated.

4. Results and discussion

Fig. 2 shows the thickness of 24 illicit and not illicit materials from different categories for 0.1% transmission for the simulated sources. Penetration capabilities were calculated using the F2 tally with NPS up to 6x10^7 histories yielding an accuracy < 1%. In the case of neutrons there is good penetration in all cases and the penetration for the heavy materials (plutonium, uranium, gold, and lead) is excellent compared to gamma or X-ray sources. In the presence of organic materials neutrons have good penetration but gamma or X-rays sources gives excellent penetration capabilities.

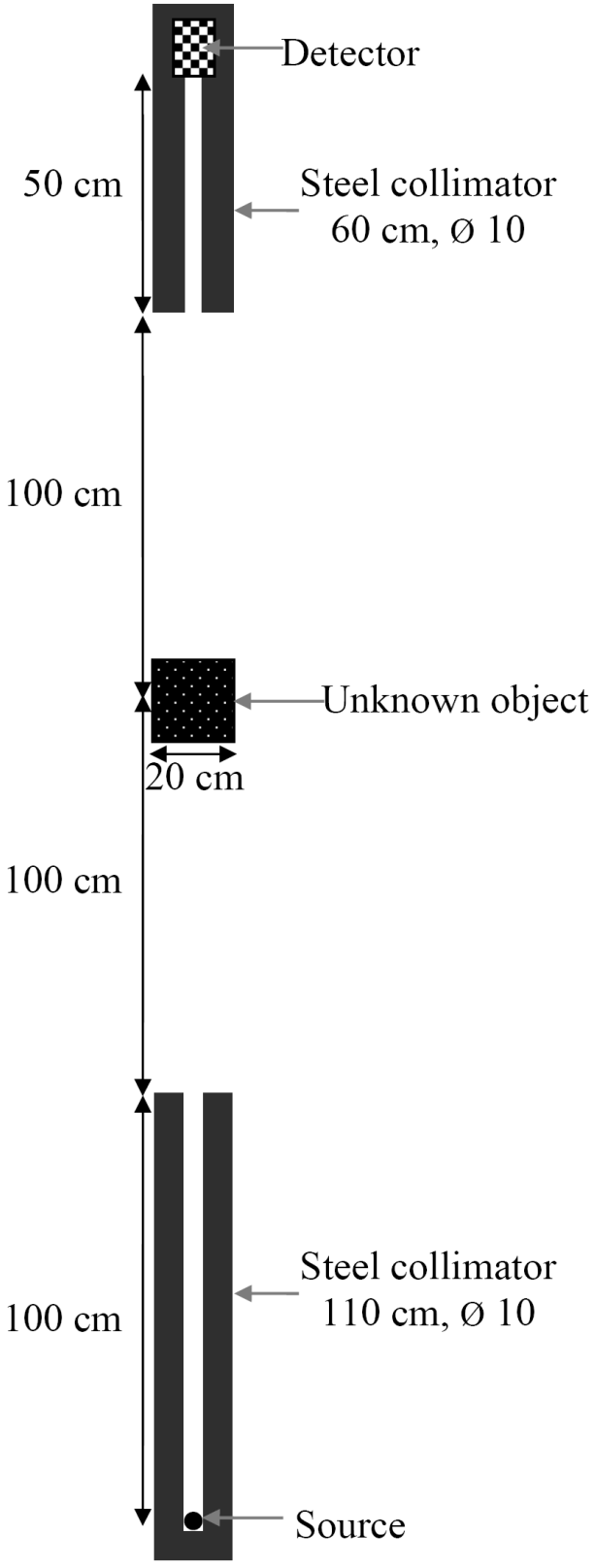

Fig. 1. The geometry for *R* values calculations (not in scale).

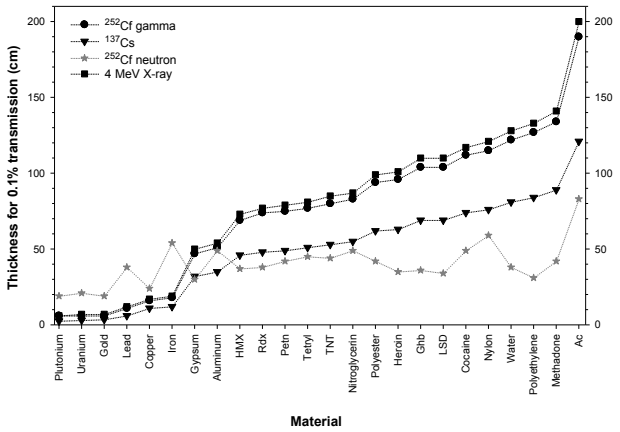

Fig. 2. Thickness for 24 materials for 0.1% transmission for the 4 sources.

The R-values of the two simulated systems namely R1 (^{252}Cf neutrons/^{252}Cf gammas) and R2 (^{252}Cf neutrons/^{137}Cs), have been considered for an extensive series of illicit and not illicit materials, [15-52]. The simulated R values are given in Table 1. In Table 1, chemical weapons are presented in bold, explosives are highlighted in underlined letters, drugs are written in italics, and non- illicit materials are in normal letters.

The major advantage of the FNGR systems is the wide range of *R* values (between polyethylene and the heaviest metals) which is also more uniformly stretch, with fine resolution between of organic materials and light and heavy metals. To demonstrate this, the two FNGR systems, compared with a dual beam X-ray system with 4 and 9 MeV X-ray sources. Fig. 3 illustrates the *R* values for the 24 materials which studied before. It is clear that both FNGR systems achieve not only the good separation within the different classes of materials (organic materials, light and heavy materials) but also permit the discrimination between organic materials. The *R* values were calculated with the MCNP4B code, using the *F1 tally card which gives the energy over a detector surface in MeV. Calculations were carried out for NPS up to $8x10^9$ histories yielding an accuracy of less than 0.08%.

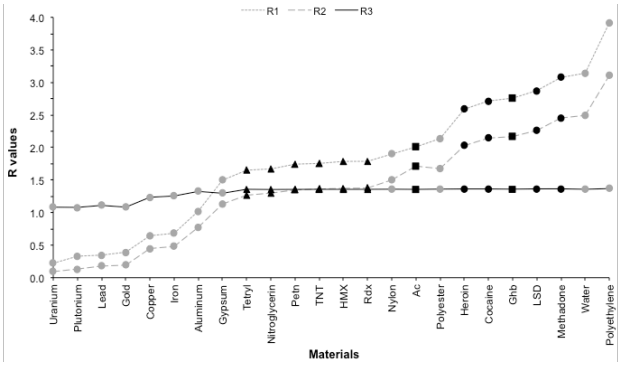

Fig. 3. The R values for the same 24 materials for different sources combinations.

Table 1. The R values of 165 materials for the 2 dual beam systems.

Material	Density	Chemical Formula	R_1	R_2
Uranium	18.97	U	0.222	0.093
Plutonium	19.74	Pu	0.330	0.134
Bismuth	9.75	Bi	0.345	0.175
Lead	11.35	Pb	0.347	0.178
Steel	7.85	From Ref. 53	0.354	0.249
Gold	19.32	Au	0.392	0.193
Silver	10.49	Ag	0.520	0.347
Copper	8.92	Cu	0.645	0.448
Iron	7.87	Fe	0.683	0.480
Silicon	2.33	Si	0.911	0.699
Calcium	1.54	Ca	0.967	0.621
Titanium Oxide	4.17	TiO_2	0.972	0.719
Ck	1.202	CNCl	0.978	0.782
Cg	1.36	$COCl_2$	0.984	0.779
Dp	1.656	$C_2Cl_4O_2$	0.991	0.776
Aluminum	2.7	Al	1.023	0.776
Glass	2.52	$Si_{4.21}Na_{1.4}Al_{0.1}O_{9.96}Ca_{0.63}$	1.032	0.777
L	1.89	$C_2H_2AsCl_3$	1.062	0.837
Magnesia-Spinel Brick	2.9	$Mg_{2.125}Al_{0.294}O_{2.567}$	1.065	0.803
Chloroform	1.48	$CHCl_3$	1.099	0.871
Concrete	2.2505	From MCNP manual, Ref. 12	1.141	0.875
Hne	1.85	$C_2N_6O_{12}$	1.183	0.913
Tnm	1.64	CN_4O_8	1.195	0.929
Md	1.836	CH_3AsCl_2	1.207	0.955
Dnaf	1.91	$C_4N_8O_8$	1.249	0.961
Pctfe	2.13	C_2ClF_3	1.268	0.977
Tntab	1.74	$C_6N_{12}O_6$	1.275	0.986
Btf	1.86	$C_6N_6O_6$	1.293	0.997
Teflon	2.2	C_nF_{2n+2}	1.418	1.087
Ptfe	2.15	C_2F_4	1.432	1.099
Dipso	1.95	$C_{12}H_4N_6O_{14}S$	1.436	1.104
Hl	1.6383	$C_{1.548}H_{2.484}Cl_{1.385}AS_{0.306}S_{0.234}$	1.463	1.156
Nona	1.7	$C_{18}H_5N_9O_{18}$	1.466	1.136
Ed	1.742	$C_2H_5AsCl_2$	1.470	1.164
Dpo	1.77	$C_{14}H_4N_8O_{13}$	1.475	1.141
Tnpy	1.77	$C_5H_2N_4O_6$	1.478	1.142
Hnab	1.6	$C_{12}H_4N_8O_{12}$	1.481	1.152
Pd	1.645	$C_6H_5AsCl_2$	1.486	1.176

Material	Density	Chemical Formula	R_1	R_2
Dips	1.89	$C_{12}H_4N_6O_{12}$	1.497	1.152
Gypsum	2.787	$CaSO_4 \cdot 2H_2O$	1.499	1.132
Tna	1.867	$C_6H_3N_5O_8$	1.499	1.158
Btx	1.87	$C_{12}H_4N_8O_{10}$	1.507	1.161
CL20	2.044	$C_6H_6N_{12}O_{12}$	1.529	1.171
Fox-7	1.885	$C_2H_4N_4O_4$	1.529	1.177
Graphite	3.51	C	1.534	1.131
Pyx	1.75	$C_{17}H_7N_{11}O_{16}$	1.535	1.187
Tacot	1.85	$C_{12}H_4N_8O_8$	1.536	1.183
Medips	1.89	$C_{13}H_6N_6O_{12}S$	1.543	1.188
Picric Acid	1.763	$C_6H_3N_3O_7$	1.559	1.205
Dipm	1.76	$C_{12}H_6N_8O_{12}$	1.569	1.212
Dpa	1.87	$C_{12}H_6N_7O_{12}$	1.579	1.215
Tenn	1.84	$C_{10}H_4N_4O_8$	1.587	1.223
Tnr	1.71	$C_6H_3N_3O_6$	1.591	1.232
Tenpo	1.86	$C_{12}H_5N_5O_9$	1.606	1.237
Dingu	1.908	$C_4H_4N_6O_6$	1.615	1.241
Dimedips	1.81	$C_{14}H_8N_6O_{12}S$	1.623	1.253
Etn	1.6	$C_4H_6N_4O_{12}$	1.630	1.267
Tetryl	1.73	$C_7H_5N_5O_8$	1.643	1.268
Torpex	1.81	$C_{1.8}H_{2.015}N_{1.663}O_{2.19}1Al_{0.6674}$	1.651	1.274
Fefo	1.59	$C_5H_6N_4O_{10}F_2$	1.653	1.286
Pato	1.94	$C_8H_5N_7O_6$	1.654	1.271
Tnpon	1.68	$C_8H_6N_4O_{10}$	1.668	1.292
Nitroglycerin (NG)	1.6	$C_3H_5N_3O_9$	1.672	1.300
Pam	1.78	$C_6H_4N_3O_6$	1.679	1.297
Datb	1.8	$C_6H_5N_5O_6$	1.709	1.318
Dadn	1.732	$C_4H_4N_4O_5$	1.719	1.320
Tnn	1.71	$C_{10}H_5N_3O_6$	1.729	1.339
Cs	1.04	$C_{10}H_5ClN_2$	1.737	1.388
Petn	1.77	$C_5H_8N_4O_{12}$	1.744	1.347
Pentolite	1.68	$C_{2.33}H_{2.37}N_{1.29}O_{3.22}$	1.753	1.357
Egdn	1.49	$C_2H_4N_2O_6$	1.756	1.371
TNT	1.654	$C_7H_5N_3O_6$	1.756	1.362
Tatb	1.93	$C_6H_6N_6O_6$	1.758	1.349
Semtex H	1.5	$C_4H_7N_5O_9$	1.766	1.377
Picratol	1.63	$C_{2.748}H_{2.325}N_{1.48}O_{2.749}$	1.766	1.371
Cyclotol-50/50	1.63	$C_{2.22}H_{2.45}N_{2.01}O_{2.67}$	1.773	1.376
Octol-60/40	1.8	$C_{2.04}H_{2.5}N_{2.15}O_{2.68}$	1.775	1.369
HMX	1.91	$C_4H_8N_8O_8$	1.787	1.373
Arsanilic Acid	1.957	$C_6H_8AsNO_3$	1.788	1.390
Keto-RDX	1,867	$C_3H_6N_6O_6$	1.788	1.375
Rdx	1.82	$(CH_2\text{-}N\text{-}NO_2)_3$	1.788	1.378
C4	1.68	$C_3H_6N_6O_6$	1.789	1.386
Dm	1.648	$C_{12}H_9AsClN$	1.789	1.405
Lx-04	1.86	$C_{1.55}H_{2.58}N_{2.3}O_{2.3}F_{0.52}$	1.796	1.381
Com B	1.72	$C_{2.03}H_{2.64}N_{2.18}O_{2.67}$	1.801	1.392
Tfna	1,692	$C_5H_7N_4O_6F_3$	1.819	1.409
Hbx-1	1.72	$C_{2.068}H_{2.83}N_{1.586}O_{2.085}Al_{0.63}$	1.820	1.408
Df	1.3595	CH_3F_2PO	1.846	1.456
Fivonite	1.59	$C_9H_{12}N_4O_{13}$	1.868	1.451
Pbx-9011	1.77	$C_{1.73}H_{3.18}N_{2.45}O_{2.6}1$	1.892	1.460
Nylon	1.15	$C_{12}H_6N_2O_4$	1.897	1.502
Tnx	1.69	$C_8H_7N_3O_6$	1.900	1.471
Petrin	1.54	$C_5H_9N_3O_{10}$	1.907	1.485
Tpeon	1.56	$C_{15}H_{24}N_8O_{26}$	1.909	1.484
Dina	1.488	$C_4H_8N_4O_8$	1.911	1.490
Pvn	1.6	$C_2H_3NO_3$	1.931	1.500
Dc	1.3338	$C_{13}H_{10}AsN$	1.953	1.558
Tnms	1.6	$C_9H_9N_3O_7$	1.976	1.535
Hnto	1.82	$C_2N_6H_6O_3$	1.981	1.525
Amatol-60/40	1.6	$C_{1.23}H_{3.88}N_{2.03}O_{3.31}$	1.993	1.547
Ac	0.687	HCN	2.009	1.714
Pps	1.43	C_6H_4S	2.026	1.609
Edna	1.65	$C_2H_6N_4O_4$	2.028	1.571
Adnt	1.497	$C_7H_7N_3O_4$	2.034	1.584
Degn	1.38	$C_4H_8N_2O_7$	2.060	1.613
Daf	1.77	$C_2N_4H_4O$	2.073	1.597
Hd	1.333	$C_4H_8C_{l2}S$	2.088	1.603
Pvc	1.38	C_2H_3Cl	2.105	1.533
Polyester	1.4	C_3H_2O	2.138	1.676
Dacron	1.37	$C_{10}H_8O_4$	2.208	1.730
Cn	1.3	C_8H_7ClO	2.223	1.751
Aspirin	1.4	$C_9H_8O_4$	2.247	1.756
Melamine	0.72	$C_3H_6N_6$	2.249	1.828
Kevlar	1.44	$C_{14}N_2O_2H_{10}$	2.250	1.755
Pppt	1.45	$C_{14}H_{10}N_2O_2$	2.250	1.755

Material	Density	Chemical Formula	R_1	R_2
Tagn	1.5	$CH_9N_7O_3$	2.266	1.763
Anfo-6/94	0.88	$C_{0.43}H_{5.54}N_{2.35}O_{3.53}$	2.286	1.837
Pbt	1.37	$C_{12}H_{12}O_4$	2.444	1.913
Pan	1.184	C_3H_3N	2.515	1.983
Orlon	1.16	$(CH_2\text{-}CHCN)_n$	2.517	1.985
Hn-1	1.086	$C_6H_{13}Cl_2N$	2.526	2.014
Mandrax	1.16	$C_{16}H_{14}N_2O$	2.526	1.988
Aspartame	1.35	$C_{14}H_{18}N_2O_5$	2.536	1.985
Sugar	0.88	$C_{12}H_{22}O_{11}$	2.558	2.052
Ht	1.263	$C_{2.74}H_{7.923}CL_{1.065}O_{0.153}S_{0.685}$	2.580	2.039
Heroin	1.34	$C_{21}H_{23}NO_5$	2.589	2.029
Men-II	1.02	$C_{2.06}H_{7.06}N_{1.33}O_{3.1}$	2.608	2.072
Wood	0.593	$C_{22}H_{31}O_{12}$	2.621	2.155
Flour	0.593	$C_6H_{12}O_6$	2.625	2.160
Benzene	0.8786	C_6H_6	2.633	2.359
Bz	1.33	$C_{21}H_{23}NO_3$	2.637	2.066
Wool	1.28	$C_{4.25}H_7NO_{1.75}S_{0.125}$	2.652	2.081
Pct	1.23	$C_{16}H_{18}O_4$	2.658	2.090
Morphine	1.31	$C_{17}H_{19}NO_3$	2.676	2.100
Cocaine	1.14	$C_{17}H_{21}NO_4$	2.716	2.145
Rice	0.702	$C_{4.15}H_{9.42}N_{0.1}O_{4.53}$	2.732	2.241
Coffee	0.4	$C_{2.24}H_{3.61}N_{0.1}O_{1.24}$	2.742	2.323
Ghb	1.21	$C_4H_8O_3$	2.759	2.169
MDA	1.08	$C_{10}H_{13}NO_2$	2.777	2.198
Tatp	1.18	$C_9H_{18}O_6$	2.839	2.236
LSD	1.21	$C_{20}H_{25}N_3O$	2.875	2.263
Acetamide	1.16	CH_3CONH_2	2.890	2.277
Vx	1.06	$C_7H_{18}NO_2PS$	2.956	2.377
ABS Plastic	1.04	$(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$	2.974	2.355
Fentanyl	1.035	$C_{22}H_{28}N_2O$	2.995	2.374
Nicotine	1.01	$C_{10}H_{14}N_2$	3.040	2.412
Methanol	0.7918	CH_3OH	3.058	2.463
Methadone	0.93	$C_21H_{27}NO$	3.077	2.455
Ppma	1.08	$C_7H_{12}O_2$	3.108	2.456
Det	1.2	$C_{14}H_{20}N_2$	3.129	2.456
Water	1	H_2O	3.143	2.494
Dxm	0.95	$C_{18}H_{25}NO$	3.147	2.505
Amphetamine	0.913	$C_9H_{13}N$	3.220	2.569
Dipt	1.05	$C_{16}H_{24}N_2$	3.235	2.557
Pbma	1.053	$C_8H_{14}O_2$	3.258	2.577
Phma	1.007	$C_{10}H_{18}O_2$	3.319	2.630
PCP	0.89	$C_{17}H_{25}N$	3.334	2.663
Ethanol	0.789	C_2H_6O	3.657	2.938
Beeswax	0.95	$C_{15}\ H_{31}\ CO_2\ C_{30}\ H_{61}$	3.909	3.102
Polyethylene	0.94	$(CH2)_n$	3.919	3.108

Based on the uncertainty values (1% on I_n/I_n^0 value and 0.1 on I_g/I_g^0 value), Table 2 shows the range for *R* value in each case for the materials which were illustrated in Fig. 3. In order to evaluate the effectiveness of the FNGR systems comparison with typical X-rays systems, the numbers of materials with overlapped R values have been calculated. Table 3 shows the percentage of materials with overlapped R values both for all materials and between of illicit and not illicit materials. The ^{252}Cf neutrons/^{137}Cs combination offers better discrimination with values 2.33% and 1.18% while the ^{252}Cf neutrons/^{252}Cf gammas combination gives similar results (3.02% and 1.96% respectively). For comparison the typical dual system based on a 4 and 9 MeV Bremsstrahlung spectra X-ray sources has 9.75% and 6.01%. The combination of the two FNGR systems improves more the effectiveness of the simulated system (1.77% and 0.89% correspondingly).

Table 2. The range for R value for 24 materials.

Material	R_1	R_1 min – max	R_2	R_2 min – max	R_3	R_3 min – max
Uranium	0.222	0.221 – 0.223	0.093	0.093 – 0.094	1.0835	1.0803 – 1.0807
Plutonium	0.330	0.329 – 0.331	0.134	0.133 – 0.134	1.0805	1.0833 – 1.0838
Lead	0.347	0.346 – 0.349	0.178	0.178 – 0.179	1.1109	1.0841 – 1.0846
Gold	0.392	0.391 – 0.393	0.193	0.192 – 0.193	1.0843	1.1105 – 1.1113
Copper	0.645	0.643 – 0.648	0.448	0.447 – 0.450	1.2359	1.3650 – 1.3542
Iron	0.683	0.680 – 0.685	0.480	0.478 – 0.481	1.2560	1.2352 – 1.2365
Aluminum	1.023	1.016 – 1.030	0.776	0.770 – 0.781	1.3255	1.2521 – 1.2536
Gypsum	1.499	1.492 – 1.506	1.132	1.127 – 1.138	1.2975	1.2955 – 1.2994
Tetryl	1.652	1.632 – 1.654	1.268	1.259 – 1.276	1.3585	1.3233 – 1.3278
Nitroglycerin	1.672	1.660 – 1.684	1.300	1.291 – 1.309	1.3555	1.3518 – 1.3592
Petn	1.744	1.733 – 1.756	1.347	1.339 – 1.355	1.3571	1.3538 – 1.3604

TNT	1.756	1.744 – 1.768	1.362	1.353 – 1.371	1.3583	1.3492 – 1.3659
HMX	1.787	1.777 – 1.798	1.373	1.366 – 1.381	1.3579	1.3548 – 1.3610
Rdx	1.788	1.777 – 1.799	1.378	1.370 – 1.386	1.3580	1.3548 – 1.3612
Nylon	1.900	1.880 – 1.914	1.502	1.489 – 1.515	1.3599	1.3547 – 1.3619
Ac	2.009	1.982 – 2.036	1.714	1.692 – 1.737	1.3575	1.3551 – 1.3620
Polyester	2.138	2.124 – 2.152	1.676	1.665 – 1.687	1.3613	1.3548 – 1.3650
Heroin	2.589	2.574 – 2.604	2.029	2.018 – 2.041	1.3637	1.3561 – 1.3654
Cocaine	2.716	2.699 – 2.734	2.145	2.132 – 2.158	1.3637	1.3572 – 1.3655
Ghb	2.759	2.742 – 2.775	2.169	2.156 – 2.181	1.3607	1.3587 – 1.3686
LSD	2.875	2.858 – 2.892	2.263	2.250 – 2.275	1.3648	1.3595 – 1.3680
Methadone	3.077	3.056 – 3.099	2.455	2.438 – 2.471	1.3657	1.3601 – 1.3694
Water	3.143	3.123 – 3.163	2.494	2.479 – 2.509	1.359	1.3597 – 1.3717
Polyethylene	3.919	3.897 – 3.941	3.108	3.092 – 3.125	1.3693	1.3637 – 1.3750

Table 3. The percentage and the number of the pairs with overlapped R values

	Dual Beam			**Triple beam**
Case	R_1	R_2	R_3	$R_1 - R_2$
Overlapped pair (total)	3.026%	2.335%	9.756%	1.776%
Overlapped pairs (between illicit – not illicit materials)	1.963%	1.181%	6.018%	0.891%

In addition, using two FNGR systems, the simulation facility offers considerable advantage in material discrimination. There are many materials with almost the same R1 or R2 values and the presence of two R values instead of one affords valuable supplementary information. For example Fig 4 shows some pairs of materials with nearly equal R1 values but different R2 values. The R1 values for these pairs varies from 0.06% to 0.34% while the respectively R2 values ranging between 1.72-15.72%. Correspondingly Fig. 5 illustrates materials couples with unequal R1 values and practically same R2 values.

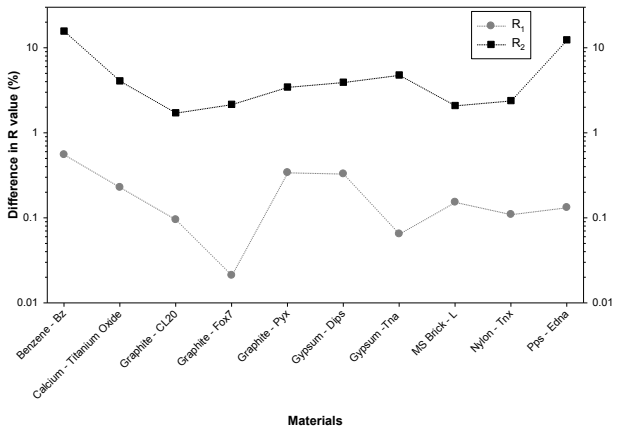

Fig. 4. Materials with nearly same R1 values but different R2 values.

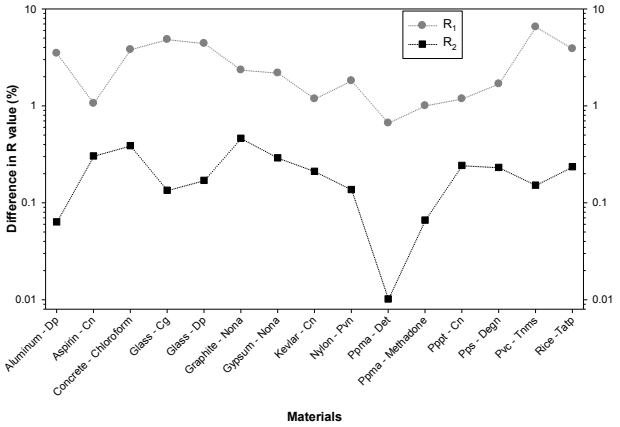

Fig. 5. Materials with nearly same R2 values but different R1 values.

5 Conclusions

A simple FNGR system based on a ^{252}Cf and ^{137}Cs isotopic sources evaluated using the MCNP4B Monte Carlo code. The evaluation has been brought into effect on the basis of the *R* values and the percentage of materials with similar *R* values was used as gauges of the effectiveness of each source mode. The two dual beam FNGR systems offer very good discriminator capabilities among a wide range of organic threat materials, narcotics and explosives while the use of three sources, instead of two, develops the capability of neutron/gamma combination to separate similar in composition materials.

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