Nuclear Instruments and Methods in Physics Research A 648 (2011) 275–284

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A transportable fast neutron and dual gamma-ray system for the detection of illicit materials

J.G. Fantidis, G.E. Nicolaou *

Laboratory of Nuclear Technology, School of Engineering, 'Democritus' University of Thrace, Vas. Sofias 12, Xanthi 67100, Greece

ARTICLE INFO

Article history:
Received 3 April 2011
Received in revised form
3 May 2011
Accepted 22 May 2011
Available online 31 May 2011

Keywords:
FNGR radiography
Triple-beam radiography
MCNP
Illicit materials

ABSTRACT

A transportable FNGR radiography system has been simulated using the MCNPX Monte Carlo code. The system is envisaged to be applied to the material characterisation of a suspicious bulky object, in view of identifying illegal materials. The system combines a neutron and two gamma-ray sources achieving characterisation of the material of the object through two ratios, namely ^{137}Cs/DD and ^{60}Co/DD. Hence, the system discriminates materials of similar or even the same of either of the two ratios. The proposed unit complies with radiation protection requirements achieving a safe occupational environment.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Recent terrorist acts, such as the 11th September 2001, have increased the necessity of monitoring objects for the detection of hidden explosive materials and hence improving security. Potential targets of such acts include buildings, events, offices, aviation and train premises. Further to these acts, the detection of illegal drugs and other substances is ratter challenging in combating crime. Places where a search for hidden illicit materials is necessary include airports, border crossing points and cargo transport [1].

In this paper, a radiography system has been modelled using MCNPX [2] for the inspection of bulky objects, in view of discrimination between different materials towards identifying illegal ones. Effectively, the system modelled extends on existing fixed systems [3,4] in two ways. Firstly, by adding a second gamma-ray energy on a combined use with the fast neutrons. The use of three, instead of two, nuclear radiations aims to achieve a better discrimination towards identifying very similar composition illegal materials hidden in the bulky object. Secondly, the system is envisaged to be transportable, bearing in mind radiation protection issues arising from the neutron and gamma-ray sources incorporated within the proposed unit. Portable neutron sources and transportable systems offer the possibility of enlarging the range of applications of neutron radiation [5,6].

* Corresponding author.
E-mail address: nicolaou@ee.duth.gr (G.E. Nicolaou).

0168-9002/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.05.063

2. Fast neutron and gamma radiography method

In Fast Neutron and Gamma Radiography (FNGR), specification of the material of an object is achieved through the evaluation of the absorption of neutrons and gamma-rays through the object. A narrow beam geometry is considered, in which case scattered radiation do not reach the detector. Hence, the transmission of the fast neutrons and gamma-rays through the object of density ρ and thickness x can be calculated by means of the following:

$$\frac{I_n}{I_n^0} = e^{-\mu_n \rho x} \tag{1}$$

and

$$\frac{I_g}{I_g^0} = e^{-\mu_g \rho x} \tag{2}$$

where μ_n and μ_g are the neutron and gamma-ray mass-attenuation coefficients, I_n and I_g are the beam intensities having emerged from the object, I_n^0 and I_g^0 are the beam intensities without the object. The ratio R is defined as

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

describes the material of the unknown object and is independent of its thickness.

3. Materials and method

3.1. The proposed system

A transportable system capable to scan bulky objects like boxes, large parcels and suitcases has been modelled. Hence, the system could be brought and used safely, according to radiation protection rules, in locations such as schools, courthouses, mailrooms, embassies, jails, government buildings, airports, army and banks. Fast scanning of the objects is essential for practical every day use. The proposed system is capable to scan objects with width and height up to 100 cm, while having a variable length. This means that except from containers, the bigger part of everyday parcels could be checked. A 3D layout of the system is shown in Fig. 1. A detailed layout, on a vertical 2D central plane section, is illustrated in Fig. 2.

The proposed radiography system, simulated using the MCNPX Monte Carlo code [2], is considered to contain a DD-110 generator, producing 10^{10} neutrons per second, for at least 2000 h [7], and the gamma-ray sources ^{137}Cs (E_γ=0.662 MeV) and ^{60}Co (E_γ=1.172 and 1.332 MeV). In detail, the proposed facility comprises (the numbering refers to Fig. 2): (1) a lead cylinder, with height and diameter of 37 cm, storing the ^{60}Co (185 GBq) source while not in use; (2) similarly, a cylinder, with height and diameter of 19 cm, for the ^{137}Cs (185 GBq) source; (3) a lead cube, with a side of 18 cm, housing the DD neutron generator and the gamma source, one at a time, when in use; the sources are brought with a simple mechanism from their storing to the irradiation position; (4) a cube, with a side of 70 cm, made of polyethylene–boron (PE–5%B) and covered by a 1 cm thick layer of lead (5); the combined PE–5%B and lead materials serve for radiation protection purposes when the sources are in use; (6) a multihole divergent steel collimator, in the form of an orthogonal trapezoidal prism, with the cavity (7) within it for placing the object under examination; along the y-axis, the cavity is 95 and 30 cm from the generator and the position detector array (8), respectively; the collimator directs the radiation from the sources towards the object scanned and eventually to the detector array position; the detector array position has dimensions of 230 and 10 cm (z- and x-axis, respectively) and is situated 230 cm away from the source at their irradiation position; the cavity, the collimator and the detector array are enclosed within a PE–5%B and lead shielding; hence, the lead shielding parts (9) and (10) are 8 and 1 cm thick; the PE–5%B parts (11), (12), (13), (14), and (15) are 35 cm thick. The overall dimensions are $71 \times 317 \times 352$ cm, while the weight is about 20000 kg. Hence, the proposed unit can be carried by a medium size lorry.

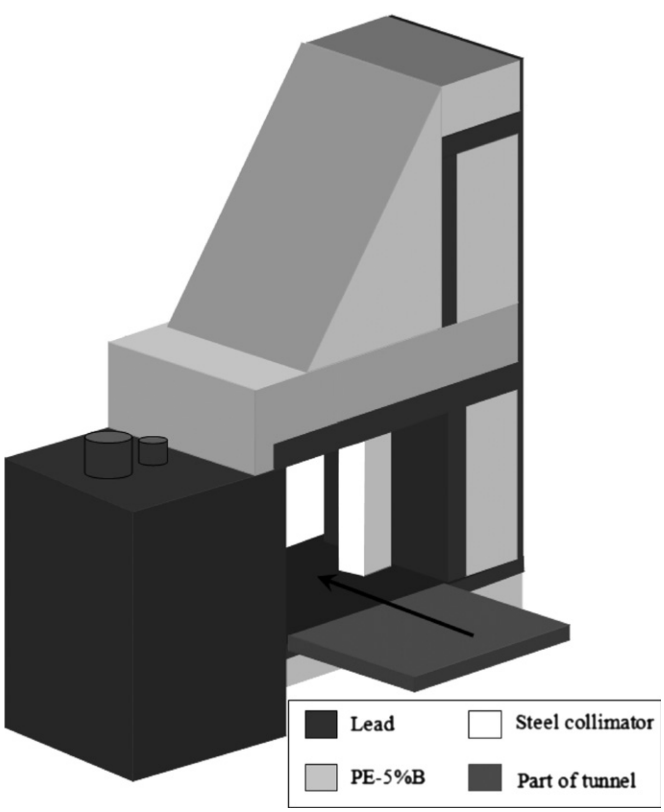

Fig. 1. A 3D view of the simulated experimental setup—not in scale.

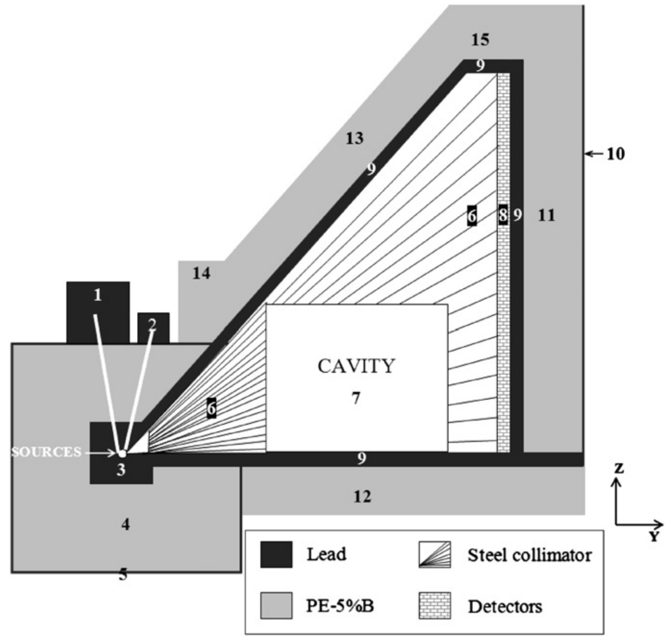

Fig. 2. Vertical 2D central plane section of the suggestion layout—not in scale.

3.2. The R values

The R-values, namely (DD/^{137}Cs) and (DD/^{60}Co), have been calculated for a wide range of explosive materials, propellants and drugs. Compositions and properties of such materials could be obtained from military books [8–11], practical handbook [12–16], scientific literature on materials [17–32], common drugs, stimulants and chemical weapons [33–39]. For comparison purposes, every day common materials such as plastics, metals, food, organic materials, fabrics and gemstones as well as nuclear materials are considered [40–50].

The top view of the facility, simulated in this work for the evaluation of the R-values, is shown in Fig. 3. It comprises an irradiation unit collimated by a cylindrical steel collimator with a length of 100 cm and diameter of 3 cm. The unit contains the neutron source for the irradiation of the object analysed. The detection of the radiation transmitted through the object is simulated through the energy that reaches a rectangular cell with dimensions $2 \times 2 \times 7.5$ cm. The cell is collimated by a steel cylindrical collimator with a length of 30 cm and a diameter of 1.5 cm. The central axes of the two collimators are along the same axis. The unknown bulk object of interest, in a cubic form with a side of 10 cm, is symmetrically placed between the collimators at a distance of 150 cm from the source and 80 cm from the cell. In the case of the gamma ray source, the geometry was the same except for the dimensions of the cell ($1 \times 1 \times 5$ cm) and the aperture of its collimation (0.75 cm). A disc source, with diameter of 3 cm, was considered in both cases emitting neutron or gamma-rays isotropically.

4. Results and discussion

The simulated *R*-values are given in Table 1 for the different materials considered. In Table 1, explosives and propellants are underlined, drugs and stimulants are in italics, chemical weapons are in bold and not illicit materials are in normal letters. The R_1- and R_2-values correspond to the ratios of the neutrons from the DD generator with the 0.662 and 1.332 MeV gamma rays from the ^{137}Cs and ^{60}Co sources, respectively. These values were calculated with the MCNPX Monte Carlo code, using the *F1 tally

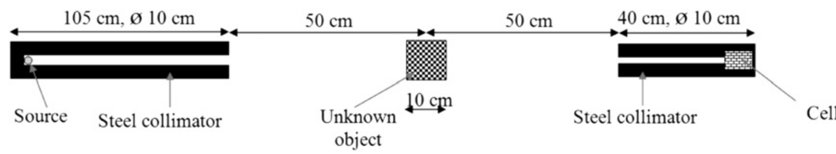

Fig. 3. The simplified geometry for *R* values calculations—not in scale (all dimensions in cm).

Table 1
Calculated *R* values for different materials (R_1 from DD/^{137}Cs sources and R_2 from DD/^{60}Co sources), explosives and propellants are written underlined, drugs and stimulants with italics, chemical weapons with bold and no illicit materials with normal letters.

Material	Density*	Chemical formula	R_1	R_2
Plutonium	19.74	Pu	0.141	0.296
Uranium	18.97	U	0.146	0.300
Thorium	11.72	Th	0.153	0.309
Bismuth	9.75	Bi	0.182	0.345
Lead	11.35	Pb	0.203	0.377
Gold	19.32	Au	0.206	0.375
Platinum	21.45	Pt	0.213	0.385
Lead dioxide	9.38	PbO_2	0.229	0.417
Hafnium	13.31	Hf	0.249	0.431
Mimetite	7.17	$Pb_5(AsO_4)_3Cl$	0.263	0.456
Vanadinite	6.95	$Pb_5(VO_4)_3Cl$	0.268	0.468
Pyromorphite	7.109	$Pb_5(PO_4)_3Cl$	0.268	0.471
Lead nitrate	4.53	$Pb(NO_3)_2$	0.300	0.507
Cadmium	8.64	Cd	0.340	0.499
Silver	10.49	Ag	0.350	0.515
Barium	3.65	Ba	0.351	0.539
Palladium	12.02	Pd	0.354	0.515
Molybdenum	10.28	Mo	0.365	0.524
Zirconium	6.51	Zr	0.377	0.536
Copper	8.92	Cu	0.402	0.554
Mercury(II) fulminate	4.43	$Hg(CNO)_2$	0.412	0.685
Zinc	7.14	Zn	0.414	0.575
Arsenic	5.727	As	0.427	0.595
Zinc oxide	5.606	ZnO	0.427	0.588
Barium perchlorate	2.74	$BaCl_2O_8$	0.455	0.647
Nickel	8.91	Ni	0.456	0.629
Iron	7.87	Fe	0.473	0.651
Steel	7.85	From Ref. [56]	0.490	0.674
Titanium oxide	4.17	TiO_2	0.514	0.700
Lead Styphnate	3.02	$C_6HN_3O_8Pb$	0.535	0.842
Titanium	4.51	Ti	0.539	0.736
Potassium perchlorate	2.52	$KCLO_4$	0.563	0.763
Silver fulminate	8.939	CAgNO	0.563	0.805
Tnm	1.64	CN_4O_8	0.564	0.761
Magnesia-zircon bricks	3.22	$Mg_{1.75}Zr_{0.115}Si_{0.117}O_{2.439}$	0.565	0.770
Potassium nitrate	2.1	KNO3	0.566	0.767
Lead azide	4.71	$Pb(N_3)_2$	0.570	0.937
Vanadium	6.09	V	0.573	0.785
Magnesia bricks	3	MgO	0.576	0.780
Hne	1.85	$C_2N_6O_{12}$	0.578	0.781
Lead picrate	2.831	$C_{12}H_4N_6O_{14}Pb$	0.597	0.908
Potassium carbonate	2.29	K_2CO_3	0.613	0.831
Magnesia-spinel brick	2.9	$Mg_{2.125}Al_{0.294}O_{2.567}$	0.613	0.831
Magnesium	1.74	Mg	0.624	0.843
Glass	2.52	$Si_{4.21}Na_{1.4}Al_{0.1}O_{9.96}Ca_{0.63}$	0.624	0.855
Hnb	1.97	$C_6N_6O_{12}$	0.639	0.863
Onc	2.3	$C_8N_8O_{16}$	0.644	0.872
Sodium nitrate	2.265	$NANO_3$	0.653	0.883
Cg	1.36	$COCl_2$	0.656	0.885
Apatite	3.19	$Ca_5(PO_4)_3(OH)_{0.33}F_{0.33}Cl_{0.33}$	0.662	0.899
Dnaf	1.91	$C_4N_8O_8$	0.662	0.895
Dp	1.656	$C_2Cl_4O_2$	0.665	0.901
Hydroxylapatite	3.156	$Ca_5(PO_4)_3(OH)$	0.683	0.927
Ddfp	2.029	$C_4N_8O_6$	0.692	0.935
Trinitromethane	1.59	CHN_3O_6	0.697	0.941
Cg	1.36	$COCl_2$	0.699	0.944
Titanium Alloys	4.42	Ti_6Al_4V	0.700	0.956

Table 1 (*continued*)

Material	Density*	Chemical formula	R_1	R_2
Dp	1.656	$C_2Cl_4O_2$	0.709	0.959
Btf	1.86	$C_6N_6O_6$	0.710	0.959
Ne	2.07	S_8	0.718	0.974
Tntab	1.74	$C_6N_{12}O_6$	0.721	0.973
Silver azide	4.42	AgN_3	0.726	1.028
Calcium	1.54	Ca	0.757	1.027
Sorguyl	1.95	$C_4H_2N_8O_{10}$	0.759	1.025
Dctb	1.93	$C_6HCl_2N_3O_6$	0.759	1.027
Spinel	3.6	$MgAl_2O_4$	0.766	1.038
Nitrogen trichloride	1.635	NCl_3	0.770	1.043
Dft	1.9	$C_4N_8O_2$	0.771	1.042
Dinitrogen tetroxide	1.443	N_2O_4	0.791	1.068
Sand (wet)	1.922	SiO_2	0.795	1.076
L	1.89	$C_2H_2AsCl_3$	0.802	1.096
Red beryl	2.68	$Be_3(AlMn)_2Si_6O_{18}$	0.803	1.090
Sodium chloride	2.16	NaCl	0.805	1.090
Abh	1.64	$C_{24}H_6N_{14}O_{24}$	0.825	1.114
Phosphophyllite	3.1	$Zn_2Fe(PO_4)_2\ 4H_2O$	0.832	1.135
Dipso	1.95	$C_{12}H_4N_6O_{14}S$	0.839	1.134
Aluminium oxide	3.97	Al_2O_3	0.842	1.142
Nona	1.7	$C_{18}H_5N_9O_{18}$	0.843	1.139
Trinitrochlorobenzene	1.85	$C_6H_2N_3O_6Cl$	0.847	1.144
Chloroform	1.48	$CHCl_3$	0.851	1.150
Concrete	2.2505	From MCNP manual, Ref. [15]	0.855	1.157
Hexanitrodiphenyloxid	1.7	$C_{12}H_4N_6O_{13}$	0.857	1.157
Hhtdd	2.07	$C_6H_5N_{12}O_{14}$	0.858	1.159
Hndpo	1.814	$C_{12}H_4N_6O_{13}$	0.859	1.161
Tnpy	1.77	$C_5H_2N_4O_6$	0.860	1.162
Hnab	1.6	$C_{12}H_4N_8O_{12}$	0.863	1.165
Aquamarine	2.72	$Be_3Al_2Si_6O_{18}$	0.863	1.170
Dpo	1.77	$C_{14}H_4N_8O_{13}$	0.868	1.170
Dnnc	1.82	$C_6H_3N_6O_8$	0.876	1.183
Dips	1.89	$C_{12}H_4N_6O_{12}$	0.877	1.185
Tna	1.867	$C_6H_3N_5O_8$	0.882	1.192
Ddnp	1.63	$C_6H_2N_4O_5$	0.896	1.210
Trinitrobenzoic acid	1.75	$C_7H_3N_3O_8$	0.898	1.213
Ck	1.202	CNCl	0.899	1.212
Ont	1.8	$C_{18}H_6N_8O_{16}$	0.901	1.217
Btx	1.87	$C_{12}H_4N_8O_{10}$	0.902	1.218
Hndp	1.64	$C_{12}H_5N_7O_{12}$	0.909	1.228
Fox-7	1.885	$C_2H_4N_4O_4$	0.918	1.241
Pyx	1.75	$C_{17}H_7N_{11}O_{16}$	0.919	1.240
Hno	1.84	$C_{14}H_6N_8O_{14}$	0.920	1.244
CL20	2.044	$C_6H_6N_{12}O_{12}$	0.921	1.244
Mannitol hexanitrate	1.604	$C_6H_8N_6O_{18}$	0.921	1.243
Baratol 70/30	2.53	$C_{2.159}H_{1.542}N_{1.154}O_{2.531}Ba_{0.115}$	0.924	1.273
Picric acid	1.763	$C_6H_3N_3O_7$	0.924	1.247
Bispicrylamino dinitro benzene	1.81	$C_{17}H_7N_8O_{16}$	0.930	1.257
Tnetb/Al(90/10)	1.75	$C_{1.399}H_{1.399}N_{1.399}O_{3.264}Al_{0.371}$	0.933	1.261
Chrysotile	2.53	$Mg_3(Si_2O_5)(OH)_4$	0.935	1.266
Md	1.836	CH_3AsCl_2	0.937	1.283
Tacot	1.85	$C_{12}H_4N_8O_8$	0.938	1.268
Adnbf	1.9	$C_6H_3N_5O_6$	0.941	1.270
Tnpid	1.83	$C_{12}H_5N_5O_{10}S$	0.945	1.276
Medips	1.89	$C_{13}H_6N_6O_{12}S$	0.947	1.279
Dipm	1.76	$C_{12}H_6N_8O_{12}$	0.948	1.280
Lx-15	1.58	$C_{3.05}H_{1.29}N_{1.27}O_{2.53}Cl_{0.04}F_{0.13}$	0.952	1.284
Dpa	1.87	$C_{12}H_6N_7O_{12}$	0.956	1.292
Tnetb/Al(80/20)	1.82	$C_{1.244}H_{1.244}N_{1.244}O_{2.902}Al_{0.715}$	0.957	1.293
Tnr	1.71	$C_6H_3N_3O_6$	0.959	1.295
Hns	1.7	$C_{14}H_6N_6O_{12}$	0.961	1.298
Etn	1.6	$C_4H_6N_4O_{12}$	0.961	1.298
Hexanitrostilbene	1.74	$C_{14}H_6N_6O_{12}$	0.961	1.299
Dpm	1.83	$C_{13}H_6N_6O_{12}$	0.963	1.300
Tenn	1.84	$C_{10}H_4N_4O_8$	0.965	1.303
Nitrotriazolone	1.93	$C_2H_2N_4O_3$	0.976	1.319
Tnetb/Al(70/30)	1.88	$C_{1.088}H_{1.088}N_{1.088}O_{2.539}Al_{1.11}$	0.983	1.329
Tenpo	1.86	$C_{12}H_5N_5O_9$	0.987	1.334
Nibtn	1.68	$C_4H_6N_4O_{11}$	0.992	1.340
Emerald	2.7	$Be_3Al_2SiO_6$	0.999	1.352
Diaminotrinitropyridine	1.844	$C_5H_4N_6O_6$	1.000	1.351
Nitroglycerin (NG)	1.6	$C_3H_5N_3O_9$	1.001	1.350
Dingu	1.908	$C_4H_4N_6O_6$	1.001	1.353
Tetryl	1.73	$C_7H_5N_5O_8$	1.009	1.365
Turquoise	2.75	$CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$	1.013	1.373
Diaminotrinitro benzoic acid	1.863	$C_7H_5N_5O_8$	1.013	1.370

Table 1 (*continued*)

Material	Density*	Chemical formula	R_1	R_2
Tetranitro octafluroamino tetraazaoctane	2.078	$C_4H_4N_{12}O_8F_8$	1.015	1.373
Trinitro hexafluroamino triazahexane	2.078	$C_3H_3N_9O_6F_6$	1.015	1.374
Gypsum	2.787	$CaSO_4 \cdot 2H_2O$	1.017	1.380
Graphite	3.51	C	1.020	1.382
Tnpon	1.68	$C_8H_6N_4O_{10}$	1.020	1.378
Dimedips	1.81	$C_{14}H_8N_6O_{12}S$	1.022	1.380
Dimehnab	1.78	$C_{14}H_8N_8O_{12}$	1.026	1.387
Picramide	1.762	$C_6H_4N_4O_6$	1.027	1.388
Dnbf	1.84	$C_3H_4N_4O_6$	1.033	1.396
Tetrytol 70/30	1.6	$C_{2.632}H_{1.88}N_{1.616}O_{2.744}$	1.041	1.406
50/50 Nm/Ccl4	1.35	$C_{1.43}H_{2.76}N_{0.92}O_{1.84}Cl_{2.05}$	1.042	1.407
Llm-105	1.98	$C_4H_4N_6O_5$	1.043	1.410
Dpe	1.81	$C_{14}H_8N_6O_{12}$	1.043	1.409
Pam	1.78	$C_6H_4N_3O_6$	1.045	1.411
95/5 PYX/polyethylene	1.556	$C_{19.33}H_{11.663}N_{11}O_{16}$	1.047	1.413
Pctfe	2.13	C_2ClF_3	1.049	1.418
BARATOL 90/10	1.65	$C_{2.775}H_{1.982}N_{1.265}O_{2.608}Ba_{0.038}$	1.049	1.426
Fefo	1.59	$C_5H_6N_4O_{10}F2$	1.051	1.420
Pato	1.94	$C_8H_5N_7O_6$	1.053	1.422
Nitrogen sulphide	1.6	N_4S_4	1.060	1.432
Nitrocellulose	1.66	$C_6H_7N_3O_{11}$	1.063	1.435
Trinitroanisole	1.61	$C_7H_5N_3O_7$	1.073	1.450
Egdn	1.49	$C_2H_4N_2O_6$	1.076	1.452
Semtex A	1.44	$C_{1.565}H_{2.533}N_{1.34}O_{3.727}$	1.077	1.452
Dadn	1.732	$C_4H_4N_4O_5$	1.078	1.457
Petn	1.77	$C_5H_8N_4O_{12}$	1.079	1.457
Hexanitro tetramine stilbene	1.764	$C_{14}H_{10}N_{10}O_{12}$	1.082	1.462
Datb	1.8	$C_6H_5N_5O_6$	1.086	1.468
Tnt/Al(67.8/32.2)	1.89	$C_{2.09}H_{1.493}N_{1.896}O_{1.791}Al_{1.193}$	1.088	1.471
Anpz	1.92	$C_4H_4N_6O_4$	1.088	1.471
Dadnpy	1.74	$C_5H_5N_5O_6$	1.089	1.472
Diamino-dinitro imidazole	1.808	$C_3H_4N_6O_4$	1.092	1.475
Daaf	1.82	$C_4H_4N_8O_3$	1.092	1.476
Tex	1.855	$C_6H_6N_4O_8$	1.095	1.480
Pentolite	1.68	$C_{2.33}H_{2.37}N_{1.29}O_{3.22}$	1.099	1.484
Tnn	1.71	$C_{10}H_5N_3O_6$	1.104	1.490
Semtex H	1.5	$C_4H_7N_5O_9$	1.106	1.493
Sdato	1.96	$C_{10}H_7N_{11}O_6$	1.107	1.495
Hnf	1.86	$CH_5N_5O_6$	1.114	1.506
Tetraniline	1.963	$C_6N_5O_2H_3$	1.117	1.510
Trinitrotoluene	*1.654*	$C_7H_5N_3O_6$	1.118	1.509
Pd	1.645	$C_6H_5AsCl_2$	1.120	1.526
Tnt/Al(89.4/10.6)	1.72	$C_{2.756}H_{1.969}N_{1.181}O_{2.362}Al_{0.393}$	1.123	1.517
Picratol	1.63	$C_{2.748}H_{2.325}N_{1.48}O_{2.749}$	1.125	1.519
Tritonal	1.72	$C_{2.465}H_{1.76}N_{1.06}O_{2.11}Al_{0.741}$	1.126	1.521
Ethyl tetryl	1.63	$C_8H_7N_5O_8$	1.127	1.522
Tnt/Al(78.3/21.7)	1.8	$C_{2.414}H_{1.724}N_{1.034}O_{2.069}Al_{0.804}$	1.128	1.525
Rdx	*1.82*	$(CH_2\text{-}N\text{-}NO_2)_3$	1.134	1.531
Nitrostarch	1.6	$C_6H_7N_3O_9$	1.135	1.533
Cyclotol-50/50	1.63	$C_{2.22}H_{2.45}N_{2.01}O_{2.67}$	1.137	1.535
Tatb	1.93	$C_6H_6N_6O_6$	1.140	1.540
Pbx-9502	1.894	$C_{6.27}H_{6.085}N_6O_6F_{0.3662}Cl_{0.123}$	1.140	1.540
Com B-3	1.72	$C_{2.04}H_{2.5}N_{2.15}O_{2.68}$	1.142	1.543
Lx-17	1.91	$C_{2.3}H_{2.19}N_{2.15}O_{2.15}Cl_{0.05}F_{0.2}$	1.142	1.543
Pbx-9503	1.9	$C_{2.16}H_{2.29}N_{2.27}$	1.142	1.543
Torpex	1.81	$C_{1.8}H_{2.015}N_{1.663}O_{2.191}Al_{0.6674}$	1.143	1.546
Octol-60/40	1.8	$C_{2.04}H_{2.5}N_{2.15}O_{2.68}$	1.144	1.545
Hl	1.6383	$C_{1.548}H_{2.484}Cl_{1.385}AS_{0.306}S_{0.234}$	1.144	1.555
Daazf	1.83	$C_4H_4N_8O_2$	1.145	1.547
Cyclotol-65/35	1.72	$C_{1.96}H_{2.53}N_{2.22}O_{2.68}$	1.145	1.547
Diglycerol tetranitrate	1.52	$C_6H_{10}N_4O_{13}$	1.145	1.546
Pbx-9407	1.6	$C_{1.41}H_{2.66}N_{2.54}O_{2.69}Cl_{0.07}F_{0.09}$	1.147	1.549
Pbx-9010	1.78	$C_{3.42}H_6N_6O_6F_{0.6354}Cl_{0.212}$	1.148	1.551
CYCLOTOL-70/30	1.73	$C_{1.87}H_{2.56}N_{2.29}O_{2.68}$	1.148	1.551
DAAT	1.76	$C_4H_4N_{12}$	1.148	1.552
CYCLOTOL-78/22	1.76	$C_{1.73}H_{2.59}N_{2.4}O_{2.69}$	1.150	1.553
OCTOL-77/23	1.81	$C_{1.76}H_{2.58}N_{2.37}O_{2.69}$	1.150	1.554
OCTOL-75/25	1.81	$C_{1.78}H_{2.58}N_{2.36}O_{2.69}$	1.150	1.554
CYCLOTOL-77/23	1.74	$C_{1.75}H_{2.59}N_{2.38}O_{2.69}$	1.150	1.554
CYCLOTOL-75/25	1.76	$C_{1.78}H_{2.58}N_{2.36}O_{2.69}$	1.150	1.554
OCTOL-78/22	1.82	$C_{1.74}H_{2.59}N_{2.39}O_{2.69}$	1.151	1.555
Ed	1.742	$C_2H_5AsCl_2$	1.156	1.580
Sodium azide	1.85	NaN_3	1.156	1.565
Rdx/Al(90/10)	1.68	$C_{1.215}H_{2.43}N_{2.43}O_{2.43}Al_{0.371}$	1.156	1.562
C4	*1.68*	$C_3H_6N_6O_6$	1.157	1.561
Rdx/Al(80/20)	1.73	$C_{1.081}H_{2.161}N_{2.161}O_{2.161}Al_{0.715}$	1.157	1.564

Table 1 (*continued*)

Material	Density*	Chemical formula	R_1	R_2
Rdx/Al(70/30)	1.79	$C_{0.945}H_{1.89}N_{1.89}O_{1.89}Al_{1.11}$	1.158	1.565
Hmx/Al(90/10)	1.76	$C_{1.216}H_{2.432}N_{2.432}O_{2.432}Al_{0.37}$	1.158	1.565
Rdx/Al(60/40)	1.84	$C_{0.81}H_{1.62}N_{1.62}O_{1.62}Al_{1.483}$	1.158	1.566
Rdx/Al(50/50)	1.89	$C_{0.675}H_{1.35}N_{1.35}O_{1.35}Al_{1.853}$	1.158	1.567
Hmx/Al(80/20)	1.82	$C_{1.08}H_{2.16}N_{2.16}O_{2.16}Al_{0.715}$	1.159	1.566
Hmx/Al(70/30)	1.86	$C_{0.944}H_{1.888}N_{1.888}O_{1.888}Al_{1.11}$	1.159	1.567
Tetranitropyrazine	1.8	$C_4H_8N_8O_8$	1.159	1.566
Hmx/Al(60/40)	1.94	$C_{0.812}H_{1.624}N_{1.624}O_{1.624}Al_{1.483}$	1.160	1.569
Anta	1.82	$C_2H_3N_5O_2$	1.160	1.566
Keto-RDX	1.867	$C_3H_6N_6O_6$	1.160	1.568
Ammonium picrate	1.72	$C_2H_6N_4O_7$	1.160	1.573
HMX	1.91	$C_4H_8N_8O_8$	1.161	1.568
Dnpen	1.6	$C_8H_7N_3O_8$	1.163	1.571
Com B	1.72	$C_{2.03}H_{2.64}N_{2.18}O_{2.67}$	1.166	1.576
Aluminium	2.7	Al	1.168	1.587
90.54/9.46 Hmx/Exon	1.833	$C_{4.63}H_{8.469}N_8O_8F_{0.4696}Cl_{0.31}$	1.169	1.580
Pbx-9404	1.84	$C_{1.4}H_{2.75}N_{2.57}O_{2.69}Cl_{0.03}P_{0.01}$	1.169	1.580
Lx-09	1.84	$C_{1.43}H_{2.74}N_{2.59}O_{2.72}F_{0.02}$	1.169	1.580
90.1/9.1 Rdx/Exon	1.786	$C_{3.544}H_{6.408}N_6O_6F_{0.408}Cl_{0.272}$	1.170	1.581
Sa	1.667	AsH_3	1.176	1.626
1,4-Dinitrobenzene	1.64	$C_6H_4N_2O_4$	1.177	1.590
Lx-10	1.86	$C_{1.42}H_{2.66}N_{2.57}O_{2.57}F_{0.17}$	1.178	1.591
Dipehn	1.63	$C_{10}H_{16}N_6O_{19}$	1.188	1.605
Ammonium dinitramide	1.812	$H_4N_4O_4$	1.188	1.607
Ammonium perchlorate	1.95	NH_4ClO_4	1.189	1.610
Pbx-9501	1.84	$C_{1.47}H_{2.86}N_{2.6}O_{2.69}$	1.192	1.611
Edc-11	1.782	$C_{1.986}H_{2.7825}N_{2.233}O_{2.6293}$	1.195	1.614
COM C-3	1.6	$C_{1.9}H_{2.83}N_{2.34}O_{2.6}$	1.198	1.618
Silicon	2.33	Si	1.200	1.627
Diaminodinitro pyrrole	1.732	$C_4H_5N_5O_4$	1.203	1.626
65/35 Rdx/Tfna	1.754	$C_{3.7}H_{6.35}N_{5.3}O_6F_{1.05}$	1.205	1.628
Lx-14	1.84	$C_{1.52}H_{2.92}N_{2.59}O_{2.66}$	1.205	1.629
Amatex-20	1.66	$C_{1.73}H_{2.99}N_{2.14}O_{2.9}$	1.208	1.632
Lx-07	1.87	$C_{1.48}H_{2.62}N_{2.43}O_{2.3}F_{0.35}$	1.213	1.639
Lx-04	1.86	$C_{1.55}H_{2.58}N_{2.3}O_{2.3}F_{0.52}$	1.215	1.641
Diaminotrinitrotoluene	1.701	$C_7H_7N_5O_6$	1.218	1.645
Fivonite	1.59	$C_9H_{12}N_4O_{13}$	1.224	1.653
Alex 32	1.88	$C_{1.647}H_{2.093}N_{1.365}O_{1.744}Al_{1.142}$	1.228	1.660
Petrin	1.54	$C_5H_9N_3O_{10}$	1.229	1.659
Ptfe	2.15	C_2F_4	1.233	1.665
Tpeon	1.56	$C_{15}H_{24}N_8O_{26}$	1.234	1.666
Lx-11	1.87	$C_{1.62}H_{2.54}N_{2.16}O_{2.16}F_{0.7}$	1.235	1.668
Destex	1.68	$C_{2.791}H_{2.3121}N_{0.987}O_{1.975}Al_{0.693}$	1.236	1.671
Dina	1.488	$C_4H_8N_4O_8$	1.243	1.677
Alex 20	1.801	$C_{1.783}H_{2.469}N_{1.613}O_{2.039}Al_{0.7335}$	1.244	1.682
Tadnpy	1.819	$C_5H_6N_6O_4$	1.246	1.685
Nylon	1.15	$C_{12}H_6N_2O_4$	1.256	1.689
Pbx-9205	1.67	$C_{1.83}H_{3.14}$	1.257	1.697
Pbx-9011	1.77	$C_{1.73}H_{3.18}N_{2.45}O_{2.61}$	1.259	1.700
Tnx	1.69	$C_8H_7N_3O_6$	1.259	1.700
Pvn	1.6	$C_2H_3N_1O_3$	1.266	1.710
Hbx-3	1.81	$C_{1.669}H_{2.1887}N_{1.22}O_{1.603}Al_{1.2977}$	1.267	1.713
Hexanitro-tetraaminebiphenyl ether	1.84	$C_{12}H_8N_{10}O_{13}$	1.270	1.717
Dmdnpy	1.63	$C_7H_7N_3O_6$	1.272	1.716
Metriol trinitrate	1.46	$C_5H_9N_3O_9$	1.275	1.721
Tfna	1.692	$C_5H_7N_4O_6F_3$	1.275	1.721
Amatex-40	1.61	$C_{1.44}H_{3.48}N_{2.09}O_{3.12}$	1.276	1.723
Eudn	1.75	$C_2H_7N_7O_5$	1.277	1.726
Edc-24	1.776	$C_{5.113}H_{10.252}N_8O_8$	1.278	1.726
Pbx-9007	1.64	$C_{1.97}H_{3.22}N_{2.43}O_{2.44}$	1.279	1.727
Tetra (Nitro-amino-azaoctane)	1.741	$C_4H_{12}N_{12}O_8$	1.293	1.746
Trinitro-2,4,6-triamino triazine	1.74	$C_3H_9N_9O_6$	1.293	1.747
Xtx-8003	1.53	$C_{1.8}H_{3.64}N_{1.01}O_{3.31}S_{0.27}$	1.293	1.746
Hbx-1	1.72	$C_{2.068}H_{2.83}N_{1.586}O_{2.085}Al_{0.63}$	1.296	1.751
1.8-Dnn	1.57	$C_{10}H_6N_2O_4$	1.298	1.752
Lx-01	1.24	$C_{1.52}H_{3.73}N_{1.69}O_{3.39}$	1.300	1.750
Methyl nitrate	1.708	CH_3NO_3	1.308	1.767
Minol	1.7	$C_{0.617}H_{2.44}N_{1.264}O_{2.029}Al_{0.741}$	1.308	1.767
Polyglycolide	1.53	$(C_2H_2O_2)_n$	1.308	1.766
Nm	1.3895	$C_2H_6S_5$	1.316	1.778
Tfena	1.523	$C_2H_3N_2O_2F_3$	1.319	1.779
Tnms	1.6	$C_9H_9N_3O_7$	1.327	1.790
Pbxn-1	1.77	$C_{1.498}H_{2.863}N_{1.971}O_{1.791}Al_{0.742}$	1.330	1.797
Amatol-60/40	1.6	$C_{1.23}H_{3.88}N_{2.03}O_{3.31}$	1.330	1.796
H-6	1.71	$C_{1.888}H_{2.589}N_{1.611}O_2Al_{0.7415}$	1.330	1.797
Pbxc-117	1.75	$C_{1.65}H_{3.138}N_{1.946}O_{2.048}Al_{0.63}$	1.342	1.814

Table 1 (*continued*)

Material	**Density***	**Chemical formula**	R_1	R_2
Xtx-8004	1.55	$C_{1.62}H_{3.76}N_{2.16}O_{2.43}S_{0.27}$	1.353	1.827
Uni	1.59	$CH_5N_3O_4$	1.354	1.828
Dnt	1.53	$C_7H_6N_2O_4$	1.356	1.829
70/30 An/Al	1.05	$H_{3.5}N_{1.75}O_{2.62}Al_{1.11}$	1.364	1.835
Arsanilic acid	1.957	$C_6H_8AsNO_3$	1.365	1.859
Comp A-3	1.64	$C_{1.87}H_{3.74}N_{2.46}O_{2.46}$	1.367	1.845
NHN	2.12	$NiH_{12}N_8O_6$	1.370	1.857
Pbxc-116	1.65	$C_{1.968}H_{3.7463}N_{2.356}O_{2.4744}$	1.370	1.850
Degn	1.38	$C_4H_8N_2O_7$	1.370	1.848
Hnto	1.82	$C_2N_6H_6O_3$	1.375	1.858
Edna	1.65	$C_2H_6N_4O_4$	1.386	1.873
Nitroguanidine	1.71	$CH_4N_4O_2$	1.387	1.874
Ethriol trinitrate	1.5	$C_6H_{11}N_3O_9$	1.391	1.878
80/20 An/Al	1.05	$H_4N_2O_3Al_{0.74}$	1.394	1.875
Cs	1.04	$C_{10}H_5ClN_2$	1.394	1.875
Dm	1.648	$C_{12}H_9AsClN$	1.399	1.901
Adnt	1.497	$C_7H_7N_3O_4$	1.399	1.888
Amatol-80/20	1.6	$C_{0.616}H_{4.44}N_{2.26}O_{3.53}$	1.400	1.891
Monomethylamine nitrate	1.225	$CH_4N_2O_3$	1.402	1.886
Pbxc-119	1.635	$C_{1.817}H_{4.1073}N_{2.2149}O_{2.688}$	1.418	1.914
95/5 NQ/estane	1.705	$C_{1.281}H_{4.3993}N_4O_{2.0987}$	1.425	1.924
90/10 An/Al	1.05	$H_{4.5}N_{2.25}O_{3.37}Al_{0.37}$	1.425	1.917
Ammonium nitrate	1.72	NH_4NO_3	1.468	1.987
Df	1.3595	CH_3F_2PO	1.476	1.989
Da	1.3875	$C_{12}H_{10}AsCl$	1.482	2.010
Diaminofurazan	1.61	$C_2H_4N_4O$	1.486	2.008
Daf	1.77	$C_2N_4H_4O$	1.490	2.012
Polyester	1.4	C_3H_2O	1.491	2.005
Ac	0.687	HCN	1.497	1.998
Nm	1.13	CH_3NO_2	1.512	2.035
1,4-Dinitro-piperazine	1.57	$C_4H_8N_4O_4$	1.525	2.060
Soybean	0.753	$C_{15}H_{10}O_4$	1.526	2.043
Tetracene	1.7	$C_2H_8N_{10}O_1$	1.529	2.067
Dc	1.3338	$C_{13}H_{10}AsN$	1.533	2.078
Guanidine nitrate	1.436	$CH_6N_4O_3$	1.538	2.074
Hydrazine nitrate	1.626	$H_5N_3O_3$	1.542	2.084
Dacron	1.37	$C_{10}H_8O_4$	1.551	2.088
Tegn	1.335	$C_6H_{12}N_2O_8$	1.553	2.095
Anfo-6/94	0.88	$C_{0.43}H_{5.54}N_{2.35}O_{3.53}$	1.562	2.095
Pps	1.43	C_6H_4S	1.567	2.113
Aspirin	1.4	$C_9H_8O_4$	1.589	2.142
Teflon	2.2	C_nF_{2n+2}	1.607	2.174
Theophylline	1.45	$C_7H_8N_4O_2$	1.607	2.168
Polyetherimide	1.27	$(C_{37}H_{24}O_6N_2)_n$	1.607	2.165
Kevlar	1.44	$C_{14}N_2O_2H_{10}$	1.634	2.206
Pppt	1.45	$C_{14}H_{10}N_2O_2$	1.636	2.205
Boron	2.46	B	1.639	2.217
Tagn	1.5	$CH_9N_7O_3$	1.645	2.222
Melamine	0.72	$C_3H_6N_6$	1.648	2.206
Cn	1.3	C_8H_7ClO	1.667	2.246
Pvc	1.38	C_2H_3Cl	1.671	2.255
Paper	0.5	$C_6H_{10}O_5$	1.671	2.167
Peek	1.35	$C_{19}H_{14}O_4$	1.688	2.273
Hd	1.333	$C_4H_8Cl_2S$	1.688	2.279
Struvite	1.7	$(NH_4)MgPO_4\cdot 6H_2O$	1.704	2.302
Paa	1.09	$C_3H_4O_2$	1.716	2.307
Hmtd	1.57	$C_6H_{12}N_2O_6$	1.720	2.283
Epichlorohydrin	1.181	C_3H_5ClO	1.728	2.330
Pvdf	1.74	$C_2H_2F_2$	1.740	2.351
Amylum	0.561	$(C_6H_{10}O_5)_n$	1.764	2.344
Pbt	1.37	$C_{12}H_{12}O_4$	1.793	2.416
Ammonium acetate	1.07	$C_2H_3O_2NH_4$	1.798	2.403
Cotton	1.55	$(C_6H_{10}O_5)_n$	1.809	2.440
Sugar	0.88	$C_{12}H_{22}O_{11}$	1.816	2.438
21/79 hydrazine/hydrazine nitrate	1.4418	$H_{6.78}N_{3.81}O_{2.5}$	1.826	2.465
Flour	0.593	$C_6H_{12}O_6$	1.830	2.436
Hn-3	1.2352	$C_6H_{12}Cl_3N$	1.833	2.471
Allobarbital	1.28	$C_{10}H_{12}N_2O_3$	1.839	2.477
Pc	1.2	$C_{16}H_{14}O_3$	1.848	2.487
Wood	0.593	$C_{22}H_{31}O_{12}$	1.853	2.468
Neoprene	1.23	$(C_4H_5Cl)_n$	1.859	2.506
Isopropyl nitrate	1.04	$C_3H_7NO_3$	1.862	2.504
Pom	1.4	CH_2O	1.868	2.517
Aspartame	1.35	$C_{14}H_{18}N_2O_5$	1.891	2.548
Men-II	1.02	$C_{2.06}H_{7.06}N_{1.33}O_{3.1}$	1.893	2.546
Mandrax	1.16	$C_{16}H_{14}N_2O$	1.896	2.560

Table 1 (*continued*)

Material	Density*	Chemical formula	R_1	R_2
Arkadite I	1.276	$C_{13}H_{12}N_2O_1$	1.904	2.566
Caffeine	1.2	$C_8H_{10}N_4O_2$	1.908	2.568
Orlon	1.16	$(CH2\text{-}CHCN)_n$	1.912	2.553
Pan	1.184	C_3H_3N	1.914	2.575
Ga	1.0756	$C_5H_{11}N_2O_2P$	1.920	2.584
Coffee	0.4	$C_{2.24}H_{3.61}N_{0.1}O_{1.24}$	1.923	2.544
Silk	1.383	$C_{12}H_{29}N_5O_{11}$	1.924	2.592
Barbital	1.24	$C_8H_{12}N_2O_3$	1.942	2.615
Heroin	1.34	$C_{21}H_{23}NO_5$	1.948	2.624
Papaverine	1.25	$C_{20}H_{21}NO_4$	1.952	2.627
Pphma	1.21	$C_{10}H_{10}O_2$	1.952	2.630
Tabun	1.0887	$C_5H_{11}N_2O_2P$	1.970	2.651
Rice	0.702	$C_{4.15}H_{9.42}N_{0.1}O_{4.53}$	1.978	2.625
Rosin	1.073	$C_{15}H_{20}O_6$	1.980	2.661
Aprobarbital	1.28	$C_{10}H_{14}N_2O_3$	1.987	2.678
Pma	1.22	$C_4H_6O_2$	1.992	2.683
Pct	1.23	$C_{16}H_{18}O_4$	2.001	2.692
Wool	1.28	$C_{4.25}H_7NO_{1.75}S_{0.125}$	2.014	2.713
Oxycodone	1.23	$C_{18}H_{21}NO_4$	2.020	2.721
Hn-2	1.118	$C_5H_{11}Cl_2N$	2.021	2.722
LSA	1.31	$C_{16}H_{17}N_3O$	2.023	2.726
Morphine	1.31	$C_{17}H_{19}NO_3$	2.043	2.748
Cocaine	1.14	$C_{17}H_{21}NO_4$	2.058	2.770
Ghb	1.21	$C_4H_8O_3$	2.060	2.774
Thebaine	1.3	$C_{19}H_{21}NO_3$	2.061	2.777
Bz	1.33	$C_{21}H_{23}NO_3$	2.067	2.785
Vinylbital	1.25	$C_{11}H_{16}N_2O_3$	2.074	2.794
MMDA	1.090	$C_{11}H_{15}NO_3$	2.081	2.801
Gb	1.0887	$C_4H_{10}FO_2P$	2.088	2.809
Codeine	1.32	$C_{18}H_{21}NO_3$	2.102	2.833
MDA	1.08	$C_{10}H_{13}NO_2$	2.119	2.851
Hn-1	1.086	$C_6H_{13}Cl_2N$	2.125	2.862
Ht	1.263	$C_{2.74}H_{7.923}CL_{1.065}O_{0.153}S_{0.685}$	2.136	2.881
Tatp	1.18	$C_9H_{18}O_6$	2.142	2.882
Pbzma	1.179	$C_{11}H_{12}O_2$	2.152	2.894
Acrylic glass	1.19	$(C_5O_2H_8)_n$	2.183	2.940
Ethyl centralite	1.112	$C_{17}H_{20}N_2O$	2.202	2.954
Amobarbital	1.17	$C_{11}H_{18}N_2O_3$	2.205	2.970
Meprobamate	1.19	$C_9H_{18}N_2O_4$	2.209	2.975
MDMA	1.04	$C_{11}H_{15}NO_2$	2.209	2.972
GF	1.1278	$C_7H_{14}FO_2P$	2.220	2.988
Mescaline	1.09	$C_{11}H_{17}NO_3$	2.224	2.993
Vx	1.06	$C_7H_{18}NO_2PS$	2.229	3.000
Acetamide	1.16	CH_3CONH_2	2.229	3.003
Nicethamid	1.062	$C_{10}H_{14}N_2O$	2.245	3.021
LSD	1.21	$C_{20}H_{25}N_3O$	2.257	3.035
Benzene	0.8786	C_6H_6	2.297	3.085
A-methyl-tryptamine	1.12	$C_{11}H_{14}N_2$	2.320	3.124
Methanol	0.7918	CH_3OH	2.325	3.118
Pema	1.119	$C_6H_{10}O_2$	2.326	3.129
Pvoh	1.26	C_2H_4O	2.334	3.144
ABS plastic	1.04	$(C_8H_8\cdot C_4H_6\cdot C_3H_3N)_n$	2.343	3.179
Ethylene glycol	1.113	$C_2H_4(OH)_2$	2.344	3.156
Fentanyl	1.035	$C_{22}H_{28}N_2O$	2.357	3.124
Pa66	1.14	$C_{12}H_{22}N_2O_2$	2.362	3.177
Water	1	H_2O	2.375	3.192
Gd	1.022	$C_7H_{16}FO_2P$	2.382	3.203
Polyurethane	1.05	$C_{25}H_{42}N_2O_6$	2.387	3.211
Buprenorphine	1.215	$C_{29}H_{41}NO_4$	2.395	3.227
Alpha.N-DMT	1.099	$C_{12}H_{16}N_2$	2.396	3.226
Nicotine	1.01	$C_{10}H_{14}N_2$	2.411	3.240
Methadone	0.93	$C_{21}H_{27}NO$	2.426	3.260
Ppma	1.08	$C_7H_{12}O_2$	2.433	3.275
Mptp	0.99	$C_{12}H_{15}N$	2.436	3.274
Polystyrene	1.05	$(C_8H_9)_n$	2.439	3.282
Beryllium	1.85	Be	2.447	3.303
Vx	1.0083	$C_{11}H_{26}NO_2PS$	2.451	3.296
A.N.N-TMT	1.08	$C_{13}H_{18}N_2$	2.461	3.310
70/30 hydrazine/hydrazine nitrate	1.14	$H_{10.33}N_{5.32}O_{0.946}$	2.469	3.327
Pchma	1.1	$C_{10}H_{16}O_2$	2.490	3.350
Dxm	0.95	$C_{18}H_{25}NO$	2.497	3.356
Det	1.2	$C_{14}H_{20}N_2$	2.518	3.392
Amphetamine	0.913	$C_9H_{13}N$	2.579	3.463
Dipt	1.05	$C_{16}H_{24}N_2$	2.609	3.512
Pbma	1.053	$C_8H_{14}O_2$	2.639	3.550
Methamphetamine	0.9	$C_{10}H_{15}N$	2.649	3.558

Table 1 (*continued*)

Material	Density*	Chemical formula	R_1	R_2
Phma	1.007	$C_{10}H_{18}O_2$	2.652	3.566
Ql	0.908	$C_{11}H_{26}NO_2P$	2.657	3.568
Nylon-6,10	1.04	$C_{16}H_{30}O_2N_2$	2.679	3.602
PCP	0.89	$C_{17}H_{25}N$	2.690	3.299
Polyamide 6–12	1.085	$C_{18}H_{34}O_2N_2$	2.737	3.679
Epoxidized soybean	0.99	$C_{57}H_{106}O_{10}$	2.748	3.696
Nylon-11	1.01	$C_{11}H_{21}ON$	2.823	3.794
Polybutadienen	0.92	C_4H_6	2.831	3.800
Hydrazine	1.01	N_2H_4	2.845	3.826
Emery 2423	4.005	$C_{57}H_{104}O_6$	2.870	3.889
Polyisoprene	0.945	C_5H_8	2.929	3.933
Ethanol	0.789	C_2H_6O	2.938	3.938
Opa	0.752	$C_{4.624}H_{13.671}O_{1.2}N_{0.475}$	3.105	4.161
Beeswax	0.95	$C_{15}H_{31}CO_2C_{30}H_{61}$	3.283	4.410
Polyethylene	0.94	$(CH_2)_n$	3.294	4.424
Hydrogen	0.084	H	11.87	15.01

* g cm^{-3}.

card which gives the energy over a detector surface in MeV. Calculations were carried out for NPS of $\leq 8\times10^9$ histories for neutrons. In the case of the gamma-rays, calculations were carried out for NPS$=4\times10^9$ histories for light materials, $\leq 5\times10^{10}$ histories for heavy metals and nuclear materials. An accuracy of less than 0.05% was achieved in all cases.

The range of the R_1- and R_2-values vary within a factor of 23.4 and 15, respectively, for the materials considered (Table 1). These factors are three and two times greater than those in the existing systems DT/^{60}Co system [3] and far better than the dual X-ray systems [51–52]. Hence, good separation is achieved within the different classes of materials, discriminating between organic materials and light and heavy metals. Furthermore, a better resolution is achieved in discriminating several materials with nearly the same R_1- or R_2-values. For example, barium perchlorate–nickel, TNM–magnesia zircon bricks, HNAB–aquamarine, graphite–TNPON, PCTFE–baratol 90/10, nylon–Pbx9205, DAF–polyester, dinitro piperazine–soybean, alumin–HMX/Exon 90.54/9.46 and other material couples with identical R_1-value but dissimilar R_2-values. Furthermore, lead styphnate–magnesium, *Heroin*–rice, gypsum–dimedips, MEN II–coffee, silicon–Rdx/TFNA 65/35, DIPSO-phosphophyllite, paper–*theophyline*, aquamarine–DPO have the same R_2-values but unequal R_1-values. Evidently, the second R_2-value offer additional information in material inspection.

The system was designed in order that the Dose Equivalent Rate (DER) would remain below the annual occupational dose limit of 0.5 Sv (or 25 μSv h^{-1}) [53] at the external surface of the unit. The total dose rate, due to the neutrons and photons, was calculated with the MCNPX Monte Carlo code, using the F2, Fm2 tallies and the DE, DF cards. The F2 tally describes the neutron flux over a surface, while the D cards convert the absorbed dose to equivalent dose. Calculations were performed with NPS$=8\times10^8$ histories for the gamma-rays and NPS$=4\times10^8$ histories for the neutrons yielding an accuracy $<1\%$. The resulting total DER at the outer surface of the lead part (10) has the maximum value of 6.7 μSv h^{-1} in the case of the ^{60}Co/DD sources with an empty cavity. The total dose, which is below the occupational dose limit, comprises the neutron and gamma-ray components with values of 5.3 and 1.4 μSv h^{-1}, respectively. The induced photons, from the interaction of the neutrons with the structural materials of the unit, result to a dose which is about three orders of magnitude less than the dose from the gamma-ray sources. Hence, the dimensions of the proposed unit render it safe with regard the occupational dose limit.

In practical terms, the proposed facility would comprise a DD neutron generator with an emission of 10^{10} neutrons per second and the ^{60}Co and ^{137}Cs gamma-ray sources of 185 GBq each. Average fluxes of 1.1×10^{-6}, 1.0×10^{-6} and 1.8×10^{-6} per starting particle have been calculated with the MCNPX at the detector array for ^{60}Co, ^{137}Cs and DD generator, respectively. All calculations were performed with the F4 tally card for NPS$=10^8$ histories (accuracy $<1\%$). Hence, in order to scan a 2.5 m container, the transportable system requires about 15–30 s for a complete scan: ∼4–8 s with the ^{137}Cs and DD sources, ∼4–8 s with the ^{60}Co and DD sources and ∼7–14 s time for other operations (replacement of the gamma-ray source and extra movement of the inspected object). It should be noted that only actual device, for FNGR in operation presently, is a fixed one requiring 60–120 s for a scan of a complete object [54–55].

5. Conclusion

An FNGR radiography system, capable to be transported, has been simulated using the MCNPX Monte Carlo code, in view of being applied to the material characterisation of a suspicious bulky object. The system is envisaged to combine a neutron and two gamma-ray sources characterising the material of the object through two ratios, namely ^{137}Cs/DD and ^{60}Co/DD. This combination has given additional capability to the system in discriminating materials of similar or even the same of either of the two ratios. Nearly, 450 materials from all categories were examined and the results showed that the proposed use of three sources offers significant advantage in discrimination between a wide range of organic threat materials, narcotics and explosives. The proposed unit complies with radiation protection requirements achieving a safe occupational environment.

References

[1] J. Yinon, Trends Anal. Chem 21 (2002) 292.
[2] D.B. Pelowitz, MCNPXTM user's manual Version 2.5.0, 2005.
[3] J.E. Eberhardt, S. Rainey, R.J. Stevens, B.D. Sowerby, J. R. Tickner, Appl. Radiat. Isot 63 (2005) 179.
[4] Y. Liu, B.D. Sowerby, J.R. Tickner, Appl. Radiat. Isot 66 (2008) 463.
[5] J.G. Fantidis, G.E. Nicolaou, N.F. Tsagas, Nucl. Instr. and Meth. A 606 (2009) 806.
[6] J.G. Fantidis, G.E. Nicolaou, N.F. Tsagas, Nucl. Instr. and Meth. A 618 (2010) 331.
[7] 〈www.adelphitech.com〉.
[8] J.C. Pennington, K.A. Thorn, L.G. Cox, D.K. MacMillan, S. Yost, R.D. Laubscher, Photochemical Degradation of Composition B and Its Components, US Army Corps of Engineers, 2007.
[9] M. Zakikhani, M.S. Dortch, J.A. Gerald, Compilation of Physical and Chemical Properties and Toxicity Benchmarks for Military Range Compounds, US Army Corps of Engineers, 2002.

[10] A. Bailey, S.G. Murray, Brassey's World Military Technology—Explosives, Propellants And Pyrotechnics, Royal military college of science Shrivenham, UK, 2000.
[11] Headquarters, Department Of The Army Technical Manual, Military Explosives, U.S. Government Printing Office, 1995.
[12] ⟨http://cameochemicals.noaa.gov⟩.
[13] ⟨http://www.chemindustry.com⟩.
[14] ⟨http://www.roguesci.org/index.html⟩.
[15] ⟨http://www.powerlabs.org/⟩.
[16] A. Aziz, The Mujahideen Explosives Handbook, O. P. M. 1998.
[17] H. Muthurajan, R. Sivabalan, M.B. Talawar, S.N. Asthana, J. Hazard. Mat A112 (2004) 17.
[18] G. Wang, H. Xiao, X. Ju, X. Gong, Propellants, Explos. Pyrotechnics 31 (5) (2006) 361.
[19] M. Chovancová, S. Zeman, Thermochim. Acta 460 (2007) 67.
[20] M.H. Keshavarz, J. Hazard. Mater 143 (2007) 437.
[21] M.H. Keshavarz, J. Hazard. Mater 147 (2007) 826.
[22] M.H. Keshavarz, J. Hazard. Mater 150 (2008) 387.
[23] M.H. Keshavarz, J. Hazard. Mater 153 (2008) 201.
[24] M.H. Keshavarz, H.R. Pouretedal, A. Semnani, Chemistry 17 (6) (2008) 470.
[25] D.M. Badgujar, M.B. Talawar, S.N. Asthana, P.P. Mahulikar, J. Hazard. Mater 151 (2008) 289.
[26] M.H. Keshavarz, J. Hazard. Mater 166 (2009) 762.
[27] M.H. Keshavarz, J. Hazard. Mater. 166 (2009) 1296;
R. Meyer, J. Köhler, A. Homburg, Explosives, Wiley-VCH Verlag GmbH, Weinheim, Germany, 2002.
[28] N. Kubota, Propellants and Explosives, Thermochemical Aspects of Cobustion, Wiley-VCH Verlag GmbH, Weinheim, Germany, 2002.
[29] T. Urbanski, The Chemistry and Technology of Explosives, vol. 1–4, Pergamon Press, Oxford, England, 1985.
[30] S. Fordham, High Explosives and Propellants, Pergamon Press, Oxford, England, 1980.
[31] J. Akhavan, The Chemistry of Explosives, The Royal Society of Chemistry, 1987.
[32] W. Wallace, FMX The Revised Black Book A Guide to Field-Manufactured Explosives, Paladin Press, 1995.
[33] C.F. Lerk, M. Lagas, J.P. Boelstra, P. Broersma, J. Pharmac. Sci 66 (10) (1977) 1480.
[34] International Narcotics Control Board, List of Narcotic Drugs Under International Control, Vienna International Centre, Vienna, 2004.
[35] R.S. Vardanyan, V.J. Hruby, Synthesis of Essential Drugs, Elsevier, 2006.
[36] K. Steven, Drug Abuse Handbook, CRC press, 1998.
[37] H.R. Kranzler, P. Korsmeyer, Encyclopedia Of Drugs, Alcohol & Addictive Behavior, vol. 1–4, Macmillan Reference USA, Gale, Cengage Learning, 2009.
[38] ⟨http://www.erowid.org/chemicals/⟩.
[39] Army, Marine Corps, Navy, Air Force, Potential Military Chemical/Biological Agents and Compounds, Active Army, Army National Guard, and US Army Reserve, January 2005.
[40] D.K. Platt, Engineering and High Performance Plastics, Rapra Technology, Shawbury, UK., 2003.
[41] S. Joseph, Polymeric Materials Encyclopedia, CRC press, 1996.
[42] ⟨www.nicnas.gov.au⟩.
[43] ⟨http://www.engineeringtoolbox.com/⟩.
[44] ⟨http://www.azom.com/default.asp⟩.
[45] ⟨http://www.agcc.jp/2005/en/index.html⟩.
[46] ⟨http://www.gemdepot.com/Default.html⟩.
[47] ⟨http://www.chemindustry.com/⟩.
[48] ⟨http://www.carbonfusion.eu/default.html⟩.
[49] ⟨http://www.polymerprocessing.com/index.html⟩.
[50] ⟨http://www.lenntech.com/home.html⟩.
[51] S. Ogorodnikov, V. Petrunin, Phys. Rev. Spec. Top.—Accel. Beams 5 (2002) 104701.
[52] Z. Chen, X. Wang, Port Technol. Int 30 (2006) 163.
[53] International Commission on Radiological Protection, Publication 26, F.D. Sowboy, ICRP, Sutton. Surrey 1977.
[54] J.E. Eberhardt, Y. Liu, S. Rainey, G.J. Roach, R.J. Stevens, B.D. Sowerby, J.R. Tickner, Fast neutron and gamma-ray interrogation of air cargo containers. International Workshop on Fast Neutron Detectors, Cape Town, April 3–6 2006.
[55] J.E. Eberhardt, A.J. McEwan, D. Milinkovic, V. Sharp, B.D. Sowerby, J.R. Tickner, Fast neutron and gamma-ray detectors for the CSIRO air cargo scanner, Cape Town, April 3–6 2006.
[56] S.C. Gujrathi, J.M. D'auria, Nucl. Instr. and Meth 100 (1972) 445.