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An Alternative Method for Screening Liquid in Bottles at Airports Using Low Energy X-ray Transmission Technique

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Since August 2006, each airline passenger has been allowed to carry only a maximum of 100 ml liquid in each container and a total of not more than 1,000 ml in carry-on luggage. This measure was adopted to prevent bringing sufficient amount of deleterious liquids such as flammable, combustible and explosive liquids into the aircraft. Several methods have been investigated and tested to screen liquids in bottles at airports but none of them has been accepted as a routine inspection method. This research introduces low energy X-ray/gamma-ray transmission technique using a small ^{238}Pu isotopic source and a compact 25 mm^3 CdTe detector. The linear attenuation coefficients of various kinds of liquids contained in bottles having different sizes and thickness at 13.6 – 43.5 keV were determined without measurement of transmitted X-rays from an empty identical container or the empty portion of the container. Attenuation factor of the container was obtained from the estimated or measured container thickness and the predetermined linear attenuation coefficient of the container material. The technique introduced here could clearly distinguish alcohol, fuel oil and other kinds of liquid from water contained in bottles and cans while its sensitivity is dependent upon radiation energy and diameter of the bottle. It could be concluded that the proposed method has potential application in screening liquids contained in bottles for aviation security but further investigation on using other X-ray sources and X-ray detectors is recommended.

Key words: X-ray, gamma-ray, liquid, airport security, aviation security, explosive

1. Introduction

In response to discovery of terrorist attempt to use liquid explosives on trans-Atlantic flights in August 2006, carrying liquid into the aircraft has been strictly controlled in all airports. Each passenger can only bring liquid in its own container of no more than 100 ml. All containers for a total of not more than 1,000 ml must be put in a single re-sealable 20 cm x 20 cm transparent plastic bag. For convenience and utmost safety, reliable methods and devices are needed to identify liquid in unopened bottles. Several methods have been introduced and tested, such as vapor and trace detection, X-ray imaging, X-ray computed tomography (CT), neutron techniques, nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI) and Raman spectroscopy[1-4]. Each method has advantages and limitations. Up to now no method has been accepted for routine inspection worldwide.

Our previous research[5] has demonstrated that the simple low energy X-ray/gamma-ray transmission

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Table 1. Relative Transmission Intensity of ^{238}Pu x-rays through different kinds of liquid contained in plastic bottle of 2.26 and 3.10 cm diameter[5)]

Liquid	Relative Transmission Intensity compared to water					
	13.6 keV		17.2 keV		20.1 keV	
	2.26 cm	3.10 cm	2.26 cm	3.10 cm	2.26 cm	3.10 cm
Water	1.00	ND*	1.00	1.00	1.00	1.00
Ethanol	3.93	ND*	1.99	2.54	1.47	1.71
Kerosene	16.82	ND*	4.00	7.62	2.19	3.20
Diesel oil	15.23	ND*	3.87	7.19	2.18	3.10
Gasohol E85	9.59	ND*	3.21	5.27	2.05	2.77
Gasohol E20	15.55	ND*	4.07	7.49	2.37	3.41
Gasohol 95	16.72	ND*	4.26	8.05	2.43	3.50
Gasoline 95	19.19	ND*	4.56	8.72	2.54	3.74

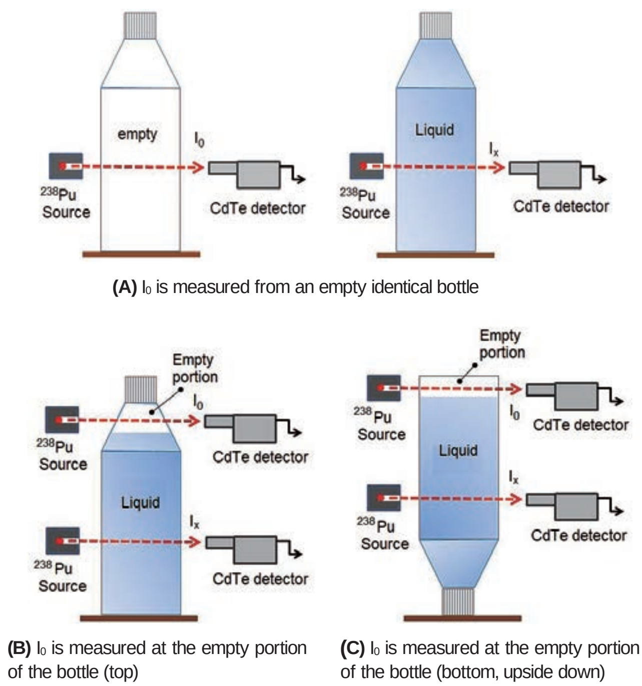

Fig. 1. Experimental set-up for measurement of I_0 and I_X in our previous report[5)].

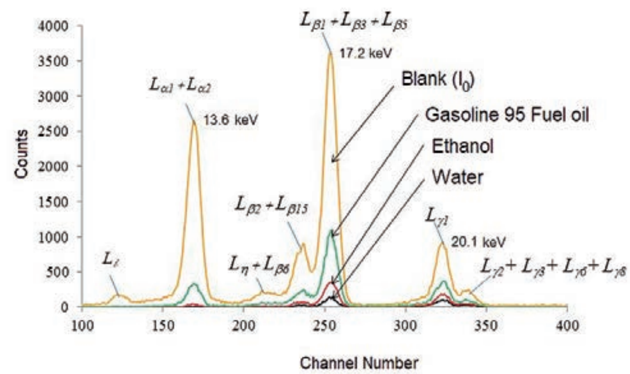

Fig. 2. Transmitted ^{238}Pu x-ray spectra through empty bottle and bottles filled with water, ethanol and gasoline 95 fuel oil.

technique could be used for screening the kind of liquid contained in a bottle when an identical bottle was available or an empty portion of bottle was present for measurement of I_0 as illustrated in Figure 1. Relative Transmission Intensity (RTI) of X-rays in 13.6 - 20.1 keV range through different kinds of liquid indicated possible use of the technique in screening liquids as showed in Table 1. For example, the RTI of X-rays for water in comparison to ethanol and gasoline 95 fuel oil contained in PET bottle with diameter of 2.26 cm were found to be approximately 1.0:3.9:19.2 at 13.6 keV and 1.0:2.0:4.6 at 17.2 keV respectively. It could be clearly seen that the sensitivity decreased significantly with increase of X-ray energy. Examples of the transmitted X-ray spectra are illustrated in Figure 2.

To use this technique for screening bottled liquid of various sizes at airport where an identical bottle may not be available and an empty portion of bottle may not present, an alternative method is needed. This research introduces a method to determine the linear attenuation coefficients of liquids contained in various sizes of containers without measurement of I_0 from an identical bottle or at an empty position of the bottle. However, this alternative method still requires information on attenuation of X-rays by the bottle or can. Methods to obtain attenuation factor by plastic and glass bottles as well as aluminum and tin-plated cans are also presented. The technique is based on the Lambert's law for transmission of X-ray and gamma-ray through matter as in equation 1.

$$I_x = I_0 e^{-\mu x} \tag{1}$$

Where I_x is the transmitted intensity through liquid, I_0 is the transmitted intensity without liquid, μ is the linear attenuation coefficient of liquid and x is thickness of liquid. The transmission factor (TF) is the ratio of I_x/I_0.

Table 2. Showing the calculated linear attenuation coefficients of some non-flammable, flammable and explosive liquids

Types of liquid/chemical formula	Density (g/cm^3)	Effective atomic number	Linear attenuation coefficient (cm^{-1})			
			13.6 keV	17.2 keV	20.1 keV	43.5 keV
Water/H_2O	1.000	7.417	2.296	0.921	0.718	0.232
Hydrogen peroxide/H_2O_2	1.054	7.687	3.496	1.383	1.071	0.327
Glycerin/$C_3H_8O_3$	1.261	6.855	2.217	0.915	0.727	0.272
Ethanol/C_2H_5OH	0.789	6.347	1.157	0.496	0.401	0.171
Methanol/CH_3OH	0.792	6.678	1.346	0.563	0.449	0.175
Acetone/C_3H_6O	0.784	6.285	1.078	0.464	0.377	0.165
Kerosene/$C_{12}H_{26}$ to $C_{15}H_{32}$	0.78 - 0.81	5.406 - 5.414	0.722 - 0.750	0.343 - 0.356	0.292 - 0.303	0.162 - 0.169
Gasoline/C_7H_{16}	0.760	5.380	0.700	0.334	0.284	0.159
Diesel oil/$C_{14}H_{30}$	0.84 - 0.87	5.411	0.778 - 0.806	0.370 - 0.383	0.314 - 0.325	0.175 - 0.181
Nitromethane/CH_3NO_2	1.137	7.183	2.197	0.889	0.699	0.242
Nitroglycerine/$CHONO_2(CH_2ONO_2)_2$	1.595	7.446	3.332	1.329	1.037	0.338
Triacetone triperoxide (TATP)/$C_9H_{18}O_6$	1.0 - 1.2	6.699	1.627 - 1.952	0.678 - 0.814	0.542 - 0.650	0.212 - 0.254

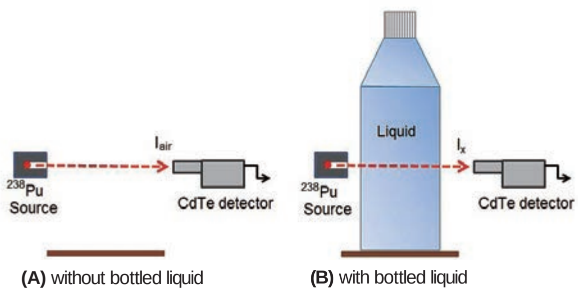

Fig. 3. Experimental set-up when measurement of I_0 is not possible: (A) measurement of Iair, (B) measurement of I_x.

For mixture, the linear attenuation coefficient (μ_{mix}) can be calculated from equation 2 below.

$$\mu_{mix} = \left[w_1 \left(\frac{\mu}{\rho}\right)_1 + w_2 \left(\frac{\mu}{\rho}\right)_2 + w_3 \left(\frac{\mu}{\rho}\right)_3 + \cdots\right] \cdot \rho_{mix} \quad (2)$$

Where ρ_{mix} is physical density of mixture; $(\frac{\mu}{\rho})_1$, $(\frac{\mu}{\rho})_2$, $(\frac{\mu}{\rho})_3$,… are mass attenuation coefficients of components number 1, 2 , 3, … and w_1, w_2, w_3,… are weight fractions of components number 1, 2, 3,… respectively. The linear attenuation coefficient of mixture (μ_{mix}) is dependent upon the weight fractions and the mass attenuation coefficients of all components as well as density of the mixture. The linear attenuation coefficients of water, hydrogen peroxide, alcohol, some flammable and explosive liquids are obtained from calculation by using equation 2 and NIST X-ray attenuation databases[6] are showed in Table 2.

2. Experimental methods and results

A 3.7 MBq (10 mCi) ^{238}Pu disc source commonly used as an exciting source in X-ray fluorescence analysis (XRF) was selected due to its small size (5 mm diameter x 5 mm thickness) and stable emission of X-rays in the range of 13.6 to 20.1 keV without need of electrical supply. The source also emits 43.5 keV gamma-rays in small percentage. The X-ray beam was collimated to 3 mm diameter whereas the transmitted X-ray intensity was measured with a compact and good resolution 5 mm x 5 mm x 1 mm CdTe detector placed 15 cm from the source aperture. The CdTe detector was connected to a digital spectrum analyzer (DSA) and a computer that performs signal processing as well as system control, spectrum display and spectrum analysis. This new method needed only a single measurement by placing a bottled liquid between the source and the detector. However, the intensity of X-rays through air (I_{air}) needed to be measured periodically to check the system stability and to be used in calculation as illustrated in Figure 3. Equation 1 could then be adapted to equations 3 below.

$$I_x = I_0\, e^{-\mu_L X_L} = I_{air}\, e^{-\mu_B \cdot 2X_B} \cdot e^{-\mu_L X_L} \quad (3)$$

Where μ_B and μ_L are the linear attenuation coefficients of bottle material and liquid; X_B and X_L are thicknesses of bottle and liquid respectively. In practice, the outside diameter (D) of bottle or can has to be measured by some means such as a Vernier caliper so that thickness of liquid (X_L) could be obtained from D-2X_B. Table 2 shows the calculated linear attenuation coefficients of some common non-flammable, flammable and explosive liquids for X-ray energies at 13.6, 17.2, 20.1 and 43.5 keV. It could be clearly seen that the lowest energy X-ray at 13.6 keV gives greatest difference of the linear attenuation coefficients among different kinds of liquid but it has the lowest penetrating power.

Various kinds of bottles and cans were firstly collected to measure their thicknesses by a Vernier caliper and the linear attenuation coefficients by X-ray transmission method including polyethylene terephthalate (PET) bottles, polyethylene (PE) bottles, glass bottles, aluminum cans and tin-plate cans. The results are

Table 3. The linear attenuation coefficients and thicknesses of common plastic bottles, glass bottles and metal cans

Container/filling liquid	Thickness (cm)	Linear attenuation coefficient (cm^{-1})			
		13.6 keV	17.2 keV	20.1 keV	43.5 keV
PET bottles/ Drinking water, fruit juice, Soy sauce, cooking oil	0.024 to 0.050	max.= 2.857 min.= 1.869 mean $\pm\sigma$ = 2.363 ± 0.572	max. =1.304 min. = 1.041 mean $\pm\sigma$ = 1.173 ± 0.161	max.= 0.508 min. = 0.387 mean $\pm\sigma$ = 0.520 ± 0.142	no data
HDPE1 bottles/ Dairy products such as milk, yogurt, soy milk, coffee	0.042 to 0.054	max.= 1.237 min. = 0.983 mean $\pm\sigma$ = 1.089 ± 0.107	max.= 0.570 min.= 0.492 mean $\pm\sigma$ = 0.533 ± 0.033	max.=0.402 min.=0.363 mean $\pm\sigma$ = 0.378 ± 0.019	no data
HDPE2 bottles/ Shower cream, shampoo	0.050 to 0.073	max.=1.703 min.=1.538 mean $\pm\sigma$ = 1.620 ± 0.109	max.= 0.924 min.= 0.837 mean $\pm\sigma$ = 0.880 ± 0.051	max.= 0.568 min.= 0.552 mean $\pm\sigma$ = 0.560 ± 0.031	no data
Glass bottles/ Beer, wine, mineral water, kerosene, fish sauce, alcohol, cooking sauce	0.350 to 0.429	ND*	max.= 13.145 min.= 11.927 mean $\pm\sigma$ = 12.434 ± 0.066	max.= 8.014 min.= 7.316 mean $\pm\sigma$ = 7.640 ± 0.058	max.= 1.220 min. = 0.957 mean $\pm\sigma$ = 1.094 ± 0.060
Aluminum cans/ Soft drink, beer, fruit juice, tea, green tea	0.009 to 0.011	max.= 31.099 min.= 30.450 mean $\pm\sigma$ = 30.824 ± 0.324	max.= 15.545 min.= 15.265 mean $\pm\sigma$ = 15.385 ± 0.168	max.= 10.208 min.= 9.360 mean $\pm\sigma$ = 9.695 ± 0.447	max.= 1.696 min. = 1.041 mean $\pm\sigma$ = 1.364 ± 0.391
Tin-plated cans/ Fruit juice, tomato paste, coffee, milk	0.019 to 0.021	ND*	ND*	max.= 146.875 min.= 144.205 mean $\pm\sigma$ = 145.294 ± 2.778	max.= 17.908 min. = 18.921 mean $\pm\sigma$ = 18.462 ± 0.684

*Notes: (1) *ND = not detectable. The x-ray energy was too low to penetrate the bottle.*
(2) The linear attenuation coefficients of each type were obtained from 5 to 10 samples.

Table 4. Showing the obtained linear attenuation coefficients of liquids contained in PET bottles of different diameters between 3 – 5 cm and thicknesses between 0.01 – 0.05 cm using the estimated thickness of 0.02 cm

Types of liquid	Linear attenuation coefficient (cm^{-1})			
	13.6 keV	17.2 keV	20.1 keV	43.5 keV
Water	I_X was too low for calculation	1.1037 ± 0.0027	0.7297 ± 0.0026	0.2369 ± 0.0060
H_2O_2 (12%)		1.1855 ± 0.0031	0.7838 ± 0.0028	0.2561 ± 0.0061
H_2O_2 (18%)		1.1947 ± 0.0032	0.7955 ± 0.0029	0.2665 ± 0.0062
Glycerin	2.0163 ± 0.0208	1.1215 ± 0.0028	0.7624 ± 0.0027	0.2886 ± 0.0063
Ethanol (95%)	1.2095 ± 0.0045	0.6578 ± 0.0012	0.4589 ± 0.0016	0.1889 ± 0.0056
Ethanol (70%)	1.4330 ± 0.0070	0.7645 ± 0.0014	0.5189 ± 0.0018	0.2039 ± 0.0057
Methanol (70%)	1.2372 ± 0.0048	0.6657 ± 0.0012	0.4607 ± 0.0016	0.1841 ± 0.0055
Acetone	1.0236 ± 0.0032	0.5559 ± 0.0010	0.3941 ± 0.0015	0.1793 ± 0.0055
Kerosene	0.7148 ± 0.0018	0.4227 ± 0.0008	0.3176 ± 0.0013	0.1815 ± 0.0055
Diesel fuel oil	0.7388 ± 0.0019	0.4292 ± 0.0008	0.3217 ± 0.0013	0.1719 ± 0.0055
Gasohol 95 fuel oil (10% ethanol)	0.7023 ± 0.0018	0.4099 ± 0.0008	0.3058 ± 0.0013	0.1672 ± 0.0055
E85 fuel oil (85% ethanol)	1.0265 ± 0.0032	0.5687 ± 0.0010	0.4006 ± 0.0015	0.1930 ± 0.0055
E20 fuel oil (20% ethanol)	0.7784 ± 0.0020	0.4443 ± 0.0008	0.3304 ± 0.0013	0.1494 ± 0.0054

Note: Explosive liquids were not available for measurement due to restriction in the country

showed in Table 3. All values were obtained from 5 to 10 samples of each with counting times between 300 to 1000 seconds depending on intensity of the interesting energy peak.

The results at 43.5 keV gamma-rays are also included because low energy X-rays could not penetrate the glass bottles and tin-plated steel cans which had very high attenuation coefficients. The final investigation was to determine the linear attenuation coefficients of liquids contained in various kinds of bottles having different materials and sizes by measurement of the transmitted X-ray intensity through bottles or cans containing the liquids. Then the linear attenuation coefficients of liquids were determined by using the mean linear attenuation coefficients of the bottle materials (the values in Table 3), the measured outside diameters of bottles by a Vernier caliper and the estimated bottle thicknesses. The results from calculation and experiment showed that the bottle thickness did not give significant error in determining the linear attenuation coefficients of liquids contained

Table 5. Showing effect of estimated thickness of plastic bottle on the obtained linear attenuation coefficients of liquids contained in 3.9 diameter PET bottles at 17.2 keV (the actual thickness is 0.06 cm)

Types of liquid	Calculated linear attenuation coefficient of liquid (cm^{-1}) using different estimated bottle thickness						
	0.02 cm	0.04 cm	0.06 cm	0.08 cm	0.10 cm	0.12 cm	0.20 cm
Water	1.1064	1.1069	1.1073	1.1078	1.1082	1.1087	1.1106
Glycerin	1.1256	1.1261	1.1660	1.1272	1.1277	1.1283	1.1306
12% H_2O_2	1.1889	1.1898	1.1906	1.1915	1.1924	1.1933	1.1970
18% H_2O_2	1.1958	1.1967	1.1976	1.1985	1.1994	1.2004	1.2042
70% Ethanol	0.7784	0.7772	0.7759	0.7746	0.7733	0.7720	0.7666
95% Ethanol	0.6708	0.6689	0.6671	0.6653	0.6634	0.6615	0.6537
70% Methanol	0.6810	0.6792	0.6774	0.6756	0.6738	0.6719	0.6644
Acetone	0.5725	0.5701	0.5678	0.5654	0.5630	0.5606	0.5506
Kerosene	0.4404	0.4374	0.4343	0.4313	0.4282	0.4250	0.4121
Diesel fuel oil	0.4502	0.4472	0.4442	0.4412	0.4381	0.4350	0.4224
Gasohol 95 fuel oil (10% ethanol)	0.4318	0.4288	0.4257	0.4226	0.4194	0.4162	0.4031
E85 fuel oil (85% ethanol)	0.5875	0.5852	0.5830	0.5807	0.5784	0.5760	0.5664
E20 fuel oil (20% ethanol)	0.4647	0.4618	0.4589	0.4559	0.4529	0.4499	0.4376

Table 6. Linear attenuation coefficients of liquids contained in glass bottles

Types of liquid	Linear attenuation coefficient (cm^{-1})		
	17.2 keV	20.1 keV	43.5 keV
Water	I_x was too low for calculation	0.6033 ± 0.0123	0.2222 ± 0.0061
18% H_2O_2		0.6673 ± 0.0132	0.2576 ± 0.0063
70% Ethanol	0.7806 ± 0.0158	0.4721 ± 0.0070	0.1819 ± 0.0051
Acetone	0.5318 ± 0.0088	0.3861 ± 0.0059	0.1555 ± 0.0050
Kerosene	0.3984 ± 0.0064	0.2949 ± 0.0047	0.1551 ± 0.0050
Diesel fuel oil	0.4307 ± 0.0063	0.3183 ± 0.0049	0.1649 ± 0.0052

in plastic bottles as showed in Tables 4, 5 and 8. This was because thickness of liquid in the bottle was several times greater than the bottle thickness and the linear attenuation coefficients of plastic bottles were close to that of the liquid. The discrepancies of the linear attenuation coefficients between the calculated values in Table 2 and from this experiment in Table 4 were mainly due to multiple X-ray peaks particularly in measurement of the peaks at 17.2 and 20.1 keV.

Glass bottles had high attenuation coefficients and their thicknesses were found to be about 0.3 to 0.5 cm. The linear attenuation coefficients at 17.2, 20.1 and 43.5 keV were found to be approximately 12.4, 7.6 and 1.1 cm^{-1} respectively which were very high compared to that of the liquid. However, the linear attenuation coefficients of different kinds of glass were found to be in a narrow range as showed in Table 3. In this investigation, the glass thickness was accurately measured by using an ultrasonic thickness gauge at the two points where the X-ray beam passed through the bottle. This was essential because the glass wall thickness was not uniform throughout the bottle. The linear attenuation coefficients of liquids contained in glass bottles were then determined by using the thicknesses measured by ultrasonic gauge, the mean values of the linear attenuation coefficients of glass (from Table 3) and the measured outside diameters of the bottles. The results were found to be lower than the values obtained from plastic bottles as shown in Table 6 but could still distinguish water from flammable liquids and fuel oils. The discrepancies were mainly due to the mean values of the linear attenuation coefficients used and the accuracy in measurement of the bottle thickness. At 17.2 keV X-ray energy and the glass bottle thickness of 0.4 cm, the error in measurement of bottle thickness of ± 0.01 and ± 0.02 cm would cause errors in the obtained linear attenuation coefficient of liquid of approximately ± 0.07 and ± 0.14 cm^{-1} respectively. The error of the linear attenuation coefficients of the glass bottle of ± 0.5 cm^{-1} would cause error in the obtained linear attenuation coefficient of liquid approximately ± 0.125 cm^{-1}. Since the transmitted intensity of lower energy X-rays were too low for precise calculation, the 43.5 keV-gamma-ray peak from the ^{238}Pu source was therefore measured and included in Table 6. Unfortunately, the peak intensity of 43.5 keV gamma-ray was very low due to its low emission probability making counting time very long. The obtained linear attenuation coefficients at 43.5 keV showed smaller difference between kinds of liquid but the penetrating power was higher.

For metal cans, including aluminum cans and tin-plated steel, the thickness and the linear attenuation coefficients were found to be rather constant. Since metal had very

Table 7. Linear attenuation coefficient (cm^{-1}) of liquids contained in metal cans

Types of liquid	Linear attenuation coefficient (cm^{-1})			
	13.6 keV	17.2 keV	20.1 keV	43.5 keV
Aluminum cans				
Water	I_x was too low for calculation	1.1036 ± 0.0046	0.7206 ± 0.0030	0.2295 ± 0.0046
Soft drink		1.1310 ± 0.0094	0.7356 ± 0.0027	0.2362 ± 0.0081
12% H_2O_2	1.5598 ± 0.0231	1.1769 ± 0.0055	0.7626 ± 0.0094	0.2392 ± 0.0047
70% Ethanol	1.0141 ± 0.0055	0.7649 ± 0.0019	0.5084 ± 0.0018	0.2045 ± 0.0044
Acetone	0.6979 ± 0.0024	0.5603 ± 0.0011	0.3866 ± 0.0013	0.1802 ± 0.0042
Kerosene	0.7442 ± 0.0027	0.4170 ± 0.0008	0.3032 ± 0.0011	0.1632 ± 0.0041
Diesel fuel oil		0.4428 ± 0.0008	0.3214 ± 0.0011	0.1778 ± 0.0042
Steel cans				
Water				0.2304 ± 0.0079
Coffee (1)				0.2380 ± 0.0091
Coffee (2)				0.2302 ± 0.0090
Coffee (3)	I_x was too low for calculation	I_x was too low for calculation	I_x was too low for calculation	0.2291 ± 0.0107
Fresh Milk				0.2365 ± 0.0064
Acetone				0.1877 ± 0.0076
Kerosene				0.1732 ± 0.0067
Diesel Fuel oil				0.1785 ± 0.0081

Table 8. Calculated transmission factors of x-rays at 15, 20, 30 and 40 keV for water, borosilicate glass and polyethylene

Material	Thickness (cm)	Transmission factor of x-rays				
		15 keV	20 keV	25 keV	30 keV	40 keV
Water	5.0	2.329×10^{-4}	1.746×10^{-2}	0.0517	0.1529	0.2615
	7.0	8.203×10^{-6}	3.456×10^{-3}	0.0158	0.0721	0.1529
	10.0	5.423×10^{-8}	3.048×10^{-4}	2.669×10^{-3}	0.0234	0.0684
Borosilicate glass	0.3	0.0305	0.2150	0.3550	0.5861	0.7480
	0.5	2.977×10^{-3}	0.0772	0.1780	0.4104	0.6163
	1.0	8.886×10^{-6}	5.962×10^{-3}	0.0317	0.1685	0.3798
Polyethylene	0.02	0.9862	0.9920	0.9935	0.9950	0.9958
	0.05	0.9659	0.9801	0.9838	0.9875	0.9895
	0.10	0.9330	0.9607	0.9679	0.9752	0.9791
Aluminum	0.01	0.8074	0.9116	0.9404	0.9701	0.9848
	0.02	0.6518	0.8310	0.8844	0.9411	0.9699
Steel	0.01	0.0113	0.1329	0.2643	0.5259	0.7518
	0.02	1.268×10^{-4}	0.0177	0.0699	0.2766	0.5653

high linear attenuation coefficients, ignoring the can thickness could cause large error in determination of the linear attenuation coefficients. Thus, attenuation of the X-ray intensity by metal cans must be taken into consideration in the same way as for the glass bottles. The linear attenuation coefficients of aluminum cans were found to be about 31.0, 15.4, 9.7 and 1.4 cm^{-1} at 13.6, 17.2, 20.1 and 43.5 keV respectively. The obtained linear attenuation coefficients of liquids contained in aluminum cans were very close to the values obtained from those of liquids inside plastic bottles particularly at 17.2 and 20.1 keV. Unfortunately, the intensities of X-rays peaks at 20.1 and 43.5 keV were too low for precise measurement. At 17.2 keV and 0.010 cm-thick aluminum can, the estimated errors of ± 0.005 and ± 0.01 cm would cause errors of the obtained linear attenuation coefficients of liquid only by ± 0.075 and ± 0.15 cm^{-1} respectively. The error from the linear attenuation coefficients of aluminum of ± 0.5, ± 1.0 and ± 2.0 cm^{-1} would cause errors of the obtained linear attenuation coefficients of liquid only about ± 0.0025, ± 0.005 and ± 0.01 cm^{-1} respectively.

The steel cans had rather constant thickness of about 0.2 cm but they had extremely high linear attenuation coefficients. The 13.6 and 17.2 keV-X-rays could not penetrate the steel cans at all. The linear attenuation coefficients of liquid could be determined only at 20.1 and 43.5 keV. Table 7 shows the results of the determination of the linear attenuation coefficients of liquids contained in aluminum and steel cans. Only 43.5 keV X-ray could penetrate the steel can and its liquid content. The obtained linear attenuation coefficients of different kinds of liquids were distinguishable but they were very close due to too high energy. For 0.020 cm thick steel can at 20.1 keV, errors from thickness measurement of ± 0.001

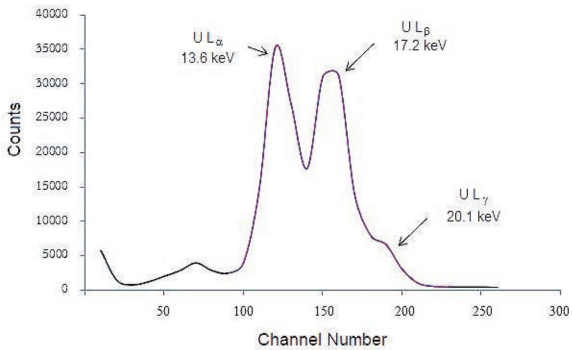

Fig. 4. ^{238}Pu x-ray spectrum measured with a Xe-filled gas proportional counter.

and 0.005 cm could cause errors of the obtained linear attenuation coefficients of liquid by ± 0.073 and ± 0.37 cm^{-1} respectively. The error from the linear attenuation coefficients of steel of 1.0 and ± 5.0 cm^{-1} would cause errors of the obtained linear attenuation coefficients of liquid of about ± 0.015 and ± 0.1 cm^{-1} respectively.

3. Discussions and conclusions

The previous paper was focused on screening liquid by using the transmission factor in comparison to that of water which was applicable only when liquid was contained in the same kind of bottle. This investigation proposes an alternative way by using the linear attenuation coefficient of liquid contained in different kinds of bottle or can which is more practical for screening liquids at airports. The results indicated that the values of the linear attenuation coefficients of liquids contained in plastic bottles were not significantly changed with the estimated bottle thicknesses as can be obviously seen in Table 5. In addition, a well-trained operator can satisfactorily distinguish the kind of plastic and estimate its thickness from its hardness which makes the liquid screening in plastic bottles reliable. However, the linear attenuation coefficients of liquid contained in glass bottles were mostly lower than the values obtained with the plastic bottles both experimentally and from calculation. This discrepancy is most probably due to accuracy in obtaining the linear attenuation coefficients of glass and the measured glass wall thickness. The statistical error in X-ray peak measurement is also an important factor because low peak intensity would result in poor peak to background ratio. This problem can be overcome by using higher activity and higher energy source such as ^{109}Cd which gives off Ag K X-rays at 22 keV (~85%), 25 keV (~15%) and 88 keV gamma-ray (3.8%) or ^{241}Am which gives off Np L X-rays at 14 keV (~13%), 18 keV (~ 19%), 21 keV (~5%), 26.35 keV gamma-ray (2.4%) and 59.6 keV gamma-ray (35%). Changing the source from ^{238}Pu will also solves the problem of Pu source restriction in many countries. As could be seen from the experimental results, energy above 20 keV may be a better choice but the energy should not exceed 40 keV. Selection of energy has to be compromised between the two factors i.e. the penetrating power and the sensitivity. Table 8 shows the calculated transmission factors of X-rays at 15, 20, 30 and 40 keV for water, borosilicate glass and polyethylene as well as aluminum and steel. It can be noticed that the energy between 20 to 30 keV will be most appropriate for this purpose depending on bottle material, thickness and diameter. Thus, ^{109}Cd and ^{241}Am sources are recommended for future investigation.

Regarding the X-ray detector, the CdTe may be replaced by a gas-filled proportional counter or a high purity germanium (HPGe) detector. The gas-filled proportional counter gives poorer energy resolution but it does not need to count all neighboring peaks separately. All neighboring peaks can be counted together as can be seen in the spectrum from our test measurement in Figure 4. The HPGe detector has the highest detection efficiency among the three detectors with the best energy resolution. However, it may not be a good option because it is costly and requires cooling by liquid nitrogen.

The proposed method has potential in screening liquids at airports but further detailed investigations are still needed particularly on changing X-ray energy between 20 to 30 keV and on testing with various kinds of liquids including liquid explosives. Unfortunately, liquid explosives are not available for the above experiments due to restriction of explosive materials in the country. Importantly, development of a data base of liquid containers and kinds of liquids is also essential before the method and equipment can be effectively applied in screening liquids in airports worldwide.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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