THEORY RESEARCH ON APPLICATION OF CT TECHNOLOGY TO SHIELDED NUCLEAR MATERIAL DISCRIMINATION

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Abstract

Smuggling of nuclear material is a serious threat to security of international society. Formal research on nuclear material discrimination can fulfil customs inspection requirement. This paper designs a situation that nuclear material which is packaged and shielded by heavy metal need to be discriminated accurately on the condition that the object being detected cannot be dismantled. Calculation results prove nuclear material could be discriminated accurately while the ideal condition is fulfilled. If multi-energy X-ray source is used the discrimination accuracy is declined. However the accuracy could be improved while energy spectrum shaping technique is used.

INTRODUCTION

Smuggling of nuclear material is a serious threat to security of international society. Until now some detecting techniques for nuclear material have already been developed which can be divided into two kinds i.e. passive and active detecting techniques. Passive detecting techniques make use of spontaneous radiation like neutron and gamma ray of nuclear material to fulfil detecting requirement. However active detecting techniques cast neutron or photon radiation on object to induce secondary radiation. Nuclear material could be detected according to the characteristic of secondary radiation from the object. Active detecting techniques include but not limited to neutron activation analysis [1], pulsed portable neutron generator interrogation systems [2], pulse fast neutron analytical method [3], nuclear resonance fluorescence analysis [4], dual energy X ray material discrimination [5], scattered photon method for nuclear material detection [6] etc. Some techniques mentioned above can detect presence of high atomic number materials, but are incompetent to affirm nuclear material directly. Others can affirm existence of nuclear material but cannot judge the quantity and position with sufficient accuracy. Even so the techniques can still fulfil detection requirements in most situations especially for custom because custom officials could dismantle pallet or dubiety piece to proceed further detection. Yet In some unparticular cases that agreement is signed that dismantlement is not allowed and precise discrimination is needed, new research work is necessary.

Dual-energy X-ray computer tomography (DECT) was put forward by Alvarez and Macovski in 1976 [7]. In recent years DECT has been applied extensively to non-destructive testing [8]. DECT utilizes two different energy X-rays to do CT scan. With reconstruction technique atomic number and electron density distribution of detected object can be calculated. Thereby material precise discrimination can be realized. Considering it can estimate position and quantity of materials too, DECT is suitable for the situation when object is not allowed to dismantle. The problem which needs to be solved is what limitation is when screening material is used and how to improve discrimination accuracy. Preliminary research work is done in this article.

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RESEARCH MODEL

In the condition of screening material existing, detection and discrimination of nuclear material is hard and complicated because lots of factors should be considered like variety and quantity of screening material, relative position of screening material with nuclear material, the kind and quantity of nuclear material etc. Any difference of these factors will influence discrimination accuracy. For facilitating research this article select Uranium-235(U235) as nuclear material and heavy metal tungsten as screening material. The incision section passing through centre of spherical research model is shown at Fig. 1.

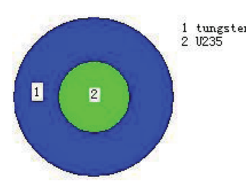

Figure 1: Research model.

MATERIAL DISCRIMINATION WITH IDEAL X-RAY SOURCE

Ideal X-ray source means ideal mono-energy X-ray source here. A simulation model is established first and nuclear material discrimination issues are discussed then.

Transmissivity Analysis

Figure 2 shows overall arrangements being built with Monte-Carlo technique [9] for calculation of transmissivity. It includes X-ray source, leading detectors and back detectors. By varying radius of U235 and size of tungsten and by increasing X-ray energy step by step, minimum energy of X-ray is recorded when back detectors collect valid data. Leading detectors act as reference which can guarantee calculation results to be precise and reliable. Calculation results are shown in Fig. 3.

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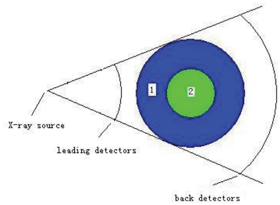

Figure 2: arrangements for transmissivity calculation.

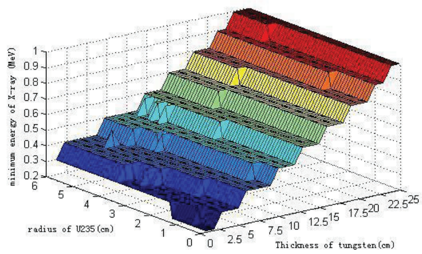

Figure 3: Minimum energy of X-ray for valid detector data.

From Fig. 3 it is observed that minimum energy of x-ray successively increases while thickness of tungsten and U235 increase and X ray whose energy is lower than 0.8MeV is incapable of producing valid data in back detectors when the thickness is larger than a certain value.

Calculation with DECT Basis Material Decomposition Method

A reconstruction algorithm is key to DECT technology. Until now many reconstruction algorithms have been developed [10-12]. Basis material decomposition method [13], hereinafter referred to as BMDM, is one useful algorithm among them. BMDM could calculate atomic number and electron density of material after decomposing attenuation coefficient of the material with attenuation coefficient of two known materials. According to energy of x-rays, BMDM can be divided as high energy and low energy. Generally high energy X-ray is referred to 1.022MeV or above which is equal to 2 times of electron rest energy [14].

Compton scatter and electron pair effect are two dominate effects produced by high energy X-ray casting on materials and electron pair effect cross section is far larger than Compton effect cross section for high atomic number material. While decomposing attenuation coefficient of material being detected, decomposition equations set will become homogeneous and valid solution of the set cannot be obtained. Therefore high energy X-ray is not suitable for high atomic number materials discrimination. Because of this reason, low energy X-ray is selected to do the following research work. According to preceding calculation，when thickness of tungsten is larger than 20 cm, X ray lower than 0.8MeV is incapable of producing valid data in back detectors. Therefore thickness of tungsten is designated as 20 cm and radius of U235 is variable.

In order to use low energy BMDM, 1MeV and 0.8MeV X ray are selected as ideal X-ray source and Carbon and Uranium as backing material. Monte-Carlo method is used to do CT simulation experiment. Attenuation coefficient distribution is calculated via reconstruction algorithm. Table 1 lists final results of atomic number(Z) and electron density(ρ_e) of tungsten and U235. Calculation proves calculation error of atomic number and electron density of U235 is too large to be used for discrimination if radius of U235 is less than 0.4 cm and calculation error is small enough to be used for discrimination if radius of U235 is larger than 0.4 cm.

Table1: Results Using Ideal X-Ray Source

radius of U235(cm)	error of Z of tungsten	error of Z of U235	error of ρ_e of U235
0.1	1.6%	11.9%	4.5%
0.2	1.6%	2.8%	1.9%
0.3	1.6%	0.6%	0.7%
0.4	1.6%	0.2%	1%
0.5	1.6%	0.3%	1%
0.6	1.6%	0.3%	1%
0.7	1.6%	0.3%	1%
0.8	1.6%	0.2%	1%

MATERIAL DISCRIMINATION WITH MULTI-ENERGY X-RAY SOURCE

The principle of multi-energy DECT BMDM is similar to ideal X-ray source. Yet process is different. Related formula is given in reference literature [15].

According to the analysis in former subparagraph the detectable radius of U235 is larger than 0.4 cm and thickness of tungsten is less than 20 cm. In following research radius of U235 is designated as 0.4 cm and thickness of tungsten as 20 cm. Using Monte-Carlo technique the X-ray spectrum produced by electron linear accelerator is calculated which is shown in Fig. 4. Two dimension CT image passing across the centre of spherical model is built at Fig. 5(left). Atomic number and electron density of tungsten and U235 is calculated using multi-energy BMDM. The results are listed in Table 2.

Table 2: Results Using Multi-Energy X-Ray Source

material	Z	error	ρ_e	error
tungsten	150.6	103.5%	14.18	8.6%
U235	143.8	56.3%	15.33	4.7%

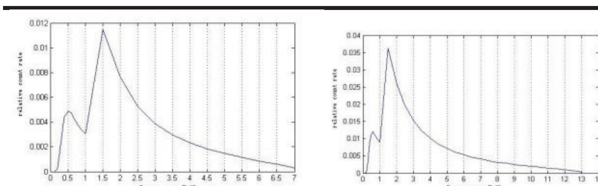

Figure 4: Multi-energy X-ray spectrums produced by electron linear accelerator, (left-7MeV, and right-13MeV).

Calculated results indicate error grow while using multi-energy X-ray source. One reason is that multi-energy X-ray spectrum has large part of low energy X-ray. When image reconstruction is done severe artifact error is produced as shown in Fig. 5(left). Artifact error causes decomposition calculation error. Energy spectrum shaping technique is a sort of efficient way to slake artifact error. Monte-Carlo technique is used for calculation of shaped energy spectrum. Appropriate energy spectrums are selected as X-ray source which are shown in Fig. 6. Image reconstruction is shown in Fig. 5(right) using the shaped energy spectrum. Atomic number and electron density of tungsten and U235 is calculated with BMDM. Calculation results are listed in Table 3. Calculation results indicate that energy spectrum shaping technique can preferably slake artifact error and increase material discrimination accuracy.

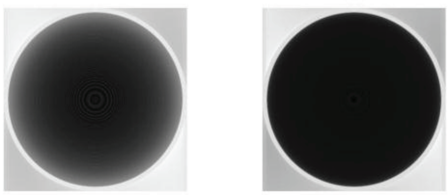

Figure 5: Image reconstructions, before energy spectrum shaping (left), after energy spectrum shaping (right).

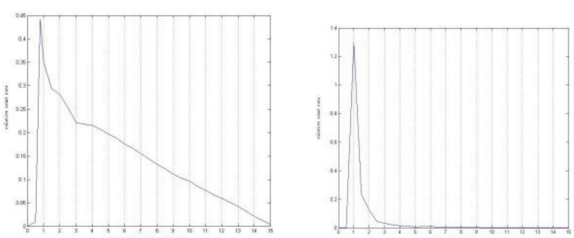

Figure 6: Shaped energy spectrum, low energy (left), high energy (right).

Table 3: Results Using Shaped Energy Spectrum

material	Z	error	ρ_e	error
W	94.33	27.5%	15.56	0.2%
U235	94.59	2.8%	16.44	13.6%

SUMMING-UPS

Nuclear material being shielded is hard to be discriminated. It is even harder while screening material is high atomic number material. Research work has been done on issues of nuclear material U235 discrimination while being shielded by tungsten. Calculation results indicate when thickness of screening material tungsten is greater than certain value or when the radius of U235 is less than certain value, X-ray DECT technology is incapable to fulfil discrimination requirement even under ideal condition. If radius of U235 and thickness of tungsten is in allowable dimensional range, DECT technology could discriminate U235 and tungsten precisely with ideal X-ray source. Using multi-energy spectrum X-ray source, DECT is less accurate to identify U235. Yet energy spectrum shaping technique could preferably slake artifact error and increase discrimination accuracy. Summing-ups above need experimental verification. Related work is still proceeding.

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