Final Report on CRP Entitled,

NEUTRON BASED TECHNIQUES FOR DETECTION OF ILLICIT MATERIALS AND EXPLOSIVES

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Summary:

Terrorist use of explosives, chemical, biological and radiological weapons has become the main source of threat to homeland security for many countries (1-4). Scanning techniques based on manual and visual inspection of large payloads at borders are ineffective from time consideration. Even inspection by X and gamma ray imaging is not a viable solution since they lose specificity; low mass attenuation coefficients for H and N, high mass attenuation coefficients for heavy elements and uncapability for distinguish nearby elements due to regular attenuation coefficients. Hence to achieve the goal of international counter-terrorism, automatic, intrusive and specific techniques must applied to inspect objects of all sizes from small parcels to large containers.

Nuclear inspection techniques based on using neutrons of different energies emitted from neutron generators and isotropic neutron sources offer a versatile and powerful inspection tool in different applications (5-9). Moreover, the experiences gained from the CRP implemented by IAEA on application of nuclear techniques for landmine detection have indicated the capability of neutron based techniques for identification of explosive materials. Hence, neutron based techniques can be used to inspect large commercial payloads for illicit trafficking.

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In this work, development, adaptation and implementation of nuclear techniques based on neutrons and gamma-rays emitted from small radioisotope sources were used to locate and identify explosive and contraband materials hidden in cargo containers. This objective was achieved by gamma or fast neutron radiography methods to locate the position of hidden object, followed by identification of the suspected object through elemental analysis by fast and thermal neutron activation. The radiography scanner and neutron identifier are combined into one complete system which is characterized by very low detection cost, mobility and ease to use by non specialists.

A short description of the designed and installed manipulating mechanical container system and radiation scanning and identification systems are given in next section.

2- Combined Scanning and Identification Systems:

The installed combined systems consist of container manipulator system, radiography scanner and neutron identifier. Figure 1 shows a schematic diagram for these systems.

FIG. 1. Schematic diagram for the installed combined systems.
2.1 Container Manipulating system:

The system consists of a transfer table moves on steel frame by step motor. Inspected container is fixed on the transfer table and is moved between radiation source and detector in step increment varies from 0.05 mm to 100 mm. The system works as well in continuous mode in the backward and forward directions. The movement increment and time of measurements are changed and adjusted by a control unit.

2.2 Radiographic Scanner:

The position of hidden object within container payload is located either by a gamma or fast neutron radiography scanner. A brief description of the installed gamma and fast neutron radiography scanners is given below:

2.2.1 Gamma-Ray Scanner:

Initial efforts were performed to install a scanning system based on gamma-ray radiography. Accordingly, a gamma scanner based on using slit beam of gamma-ray emitted from $^{60}$Co source was built and tested. A $^{60}$Co gamma source of 0.5 Ci activity was fixed in a lead shield with horizontal channel where gamma-ray collimators can be inserted to have gamma-ray beams of different geometries. The gamma-rays transmitted through the inspected container are measured by NaI(Tl) detector housed in lead shield with slit collimator fixed in front of the detector lead shield to enhance the spatial resolution of the 2D image constructed from the transmitted gamma beam.

The output signals of NaI(Tl) detector were amplified and fed to the input of a radiation analyzer to only count signals of gamma-rays of energy ranges from 1.1 to 1.4 MeV. The output of scan is fed to a counter/timer Nim module type, Ortec 776, and its output is fed to the input of PC for signal processing and image reconstruction.
2.2.2 Fast Neutron Scanner:

To improve the performance of scanning system for detection of objects hidden within thick and high dense materials, a fast neutron radiography system was installed and tested. This system works by using slit collimated beam of fast neutrons of 10 mm width and 20 mm height emitted from Pu-α-Be neutron source. The transmitted fast neutron beam was measured by stilbene scintillator fixed in high density polyethylene shield with slit collimator has the same dimensions of the incident neutron beam. Figure 2 shows the circuit diagram of neutron/gamma spectrometer used to measure fast neutron transmitted through the inspected container.

To have a good quality image by fast neutron radiography a fast neutron source with high emission rate and neutron detector of high efficiency must be used. These two requirements could not be achieved in the installed fast neutron radiography scanner which uses 5 Ci Pu-α-Be source and organic scintillator with efficiency less than 20% for neutrons of average energy ~ 4 MeV. The incident fast neutron flux was enhanced by surrounding the Pu-α-Be source directly with lead of spherical shape to work as fast neutron reflector.

The fast neutron count rate given by the neutron gamma spectrometer was only measured for fast neutrons of energies higher than 3 MeV to avoid artifact in the 2D image due to neutron multiple scattering.

![FIG.2. The circuit used in association with stilbene detector.](image)
2.3 Neutron Identifier:

The installed neutron identifier makes use of the same neutron source and gamma detector built in fast neutron and gamma radiography scanner. The output of the detector amplified signals was fed to the input of a multichannel analyzer for gamma spectrum display. The prompt emitted gamma-ray spectrum emitted from the suspected object was measured for 600 sec. Measurements were then repeated for the same time to measure gamma-ray spectrum emitted from a position far from the allocated suspected object and the given spectrum is used as background object.

3- Results and Discussion:

The cross-sectional 2D images for ATM with 2.5 kg explosive material hidden in a container filled with foam material are constructed from the measured transmitted gamma-rays and fast neutrons using MATLAP 7.0 program. Measurements were performed with bare object and with the object screened in steel box with wall thickness = 1 cm.

3.1 Gamma Scanning:

Fig. 3. Shows the constructed images for bare and steel screened ATM. The displayed images give a good indication about the position of the hidden object inside the inspected container.

3.2 Fast Neutron Scanning:

The images constructed from fast neutron radiography using 14 MeV neutrons and fast neutrons emitted from Pu-α-Be and $^{252}$Cf sources are given in figures 4, 5 and 6. The displayed
images indicate the good capability of the neutron scanner using fast neutrons emitted from radioisotopic sources. They also indicate that the images obtained with Pu-α-Be neutron source are much better than that obtained with $^{252}$Cf neutrons and are nearly of the same quality as those obtained by 14 MeV neutrons.

FIG. 4. 2D - images constructed from 14 MeV neutron scanning of ATM hidden inside cargo container.

FIG. 5. 2D - images constructed from Pu-Be neutron scanning of ATM hidden inside cargo container.

FIG. 6. 2D - images constructed from $^{252}$Cf neutrons scanning of ATM hidden inside cargo container.
3.3 Neutron Identification:

The net spectra of gamma rays resulting from fast and thermal neutron interactions with bare ATM and ATM (2.5 kg explosive) placed in steel box with walls of 1 cm thick are displayed in figures 7, 8 and 9. The spectra displayed in these figures are emitted when the object was interrogated by 14 MeV neutrons and neutrons emitted from Pu-α-Be and $^{252}$Cf sources respectively.

The spectra of gamma rays displayed in figure 7 are for gamma rays emitted from the bare and steel screened objects interrogated by 14 MeV neutrons. These two spectra show several gamma lines of energy varies from 1 to 7 MeV for gamma rays produced from the interaction of fast neutrons with the nuclei of explosive material, i.e., $^1$H, $^{12}$C, $^{14}$N and $^{16}$O.

![FIG.7. Gamma ray spectrum of ATM with 2.5 kg explosive material interrogated with 14 MeV neutrons.](image)

Figure 8 shows the net gamma ray spectra of the same ATM interrogated by Pu-α-Be neutron sources. These spectra show as well several gamma lines of energy varies from 2 to 7 MeV. These gamma lines are attributed to gamma rays produced from the interaction of fast and thermal neutrons with the nuclei of explosive material, i.e. $^1$H, $^{12}$C, $^{14}$N, and $^{16}$O.
Fig. 8. Gamma ray spectrum of ATM with 2.5 kg explosive material interrogated with Pu-α-Be neutrons.

Figure 9 shows the net gamma ray spectra for the same ATM without and with steel box interrogated by $^{252}$Cf neutrons. The displayed spectra show only the gamma line of 2.23 MeV emitted from $^1$H, the annihilation line of 0.511 MeV and 0.860 MeV emitted from $^{56}$Fe nuclei of the steel box by inelastic scattering.

The measured net gamma spectra displayed in the previous figures show that the screening of the hidden object by element of high inelastic scattering cross sections tends to enhance the moderation of fast neutrons and hence decreases the number of gamma photons emitted by inelastic scattering with $^{12}$C and $^{16}$O. However, screening the object by steel
decreases the number of gamma photons produced from thermal neutron capture. These phenomena are clearly observed from the net count rate of gamma rays emitted from different interactions by fast and thermal neutrons with the object nuclei as shown from the count rate of the gamma peak tabulated in Table 1.

Table 1. Gamma energies emitted by fast and thermal neutron interactions using different radioisotope sources

<table>
<thead>
<tr>
<th>Element</th>
<th>Reactions</th>
<th>$E_{\gamma}$ MeV</th>
<th>14 MeV neutrons</th>
<th>Pu-α-Be neutrons</th>
<th>$^{252}$Cf neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bare Object</td>
<td>Screened by steel</td>
<td>Bare Object</td>
</tr>
<tr>
<td>$^1$H</td>
<td>(n,γ)</td>
<td>2.223</td>
<td>280</td>
<td>725</td>
<td>600</td>
</tr>
<tr>
<td>$^{12}$C</td>
<td>(n,n’γ)</td>
<td>4.438</td>
<td>225</td>
<td>390</td>
<td>220</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>(n,n’γ)</td>
<td>1.640</td>
<td>320</td>
<td>625</td>
<td>900</td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>(n,n’γ)</td>
<td>6.130</td>
<td>180</td>
<td>225</td>
<td>120</td>
</tr>
<tr>
<td>$^{26}$Fe</td>
<td>(n,n’γ)</td>
<td>0.860</td>
<td>0</td>
<td>1500</td>
<td>0</td>
</tr>
</tbody>
</table>

Conclusions:

- The installed combined scanning and identification systems prove a good capability to locate the position and identify the material of hidden object in cargo containers. The scanning system can work by either gamma or fast neutron radiography technique, with nearly the same effectiveness.
- The use of fast neutron radiography with neutrons emitted from Pu-α-Be sources to scan cargo-containers show the same reliability and easiness as those work with gamma emitted from $^{60}$Co source. The use of these neutrons to radiograph objects gives nearly the same image quality obtained by 14 MeV neutron or neutrons of like fission neutron spectrum emitted from $^{252}$Cf neutron sources.
- Although fast neutrons emitted from α-Be sources are less capable to detect carbon and oxygen than 14 MeV neutrons, they are much easier to moderate and hence become more capable to identify elements by thermal neutron activation analysis.
- The effectiveness of a scanner works with isotopic fast neutron source can be enhanced to ~40% if the source is surrounded by fast neutron reflector made of heavy material.
A combined systems work with only one simple isotopic neutron source possess very low scanning cost, reduced source shield, low weight and possibility to use as mobile scanning system.

Recommendations:

- Fast neutron sources of high emission rate $\sim 10^{10}$ n/s and fast neutron detector of higher detection efficiency must be used to improve the scanning performance. With such a neutron source and neutron detector, it becomes possible to scan a container of relatively large volume in shorter time.
- Fan beam of fast neutrons and an array of radiation detectors must be installed and used to provide quick scanning of the suspected object hidden in container of various sizes.
- Further investigations have to be performed to check the effectiveness of the installed combined system for locating and identifying fertile and fissile materials hidden in cargo containers.

References: