DETECTION OF EXPLOSIVES AND OTHER ILLICIT MATERIALS IN CONTAINERS BY NANOSECOND NEUTRON ANALYSIS (NNA)

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1 SCIENTIFIC SCOPE THE PROJECT

The following problems were addressed in the framework of the Contract #13474 under present CRP:

1. Testing of the NNA/APT hardware:

2. Development and testing algorithms and software for:

3. Test measurements with simulants of hazardous materials in different scenarios.

2 THE RESULTS OBTAINED TILL NOW UNDER THE CRP

2.1 HARDWARE

2.1.1 Associated particle detectors

Inspection of large volumes by NNA-based devices requires associated particle detectors with large number of pixels. A single plate p-i-n diode detector subdivided into 144 pixels has been designed and produced for this purpose. This detector was installed into an ING-27 neutron generator produced by All-Russia Research Institute of Automatics (VNIIA). A new version of the NG control software has been developed, debugged and successfully tested.

A new type of the associated alpha-particle detector based on CVD diamond has been made and tested. Such detectors have much higher radiation stability than silicon-based types, can operate at higher temperatures, and have much shorter signals (1-2ns). A preamplifier with wider frequency band (~1GHz) has been developed to allow amplification of fast signals.
After that the signals from CVD diamond detectors can be included into the existing NNA data acquisition system.

Several portable neutron generators (producer – VNIIA, Russia) with different types of built-in position-sensitive associated particle detectors (from 9 to 144 pixels) have been tested. The NG intensities varied from $3 \times 10^7$ n/s to $10^8$ n/s. Silicon-based associated particle detectors were shown to have close to 100% intrinsic efficiency for alpha-particles.

### 2.1.2 Gamma- and neutron detectors

Three types of gamma detectors (based on BGO, NaI, and LaBr$_3$ crystals) were compared to each other. At present 12 detector modules based on BGO, one LaBr$_3$ and one NaI-based are connected to data acquisition system.

LaBr$_3$ crystal has very good energy and time resolution compared to NaI and BGO crystals, but not as good as that of HPGe detectors. However, due to its high density, LaBr$_3$ has much higher detection efficiency than HPGe when detecting gamma-quanta of high energies.

![Figure 1. Spectra of γ-rays from oxygen and aluminium irradiated with 14 MeV neutrons (NNA technique) for detectors based on 3”×3” BGO and 3”×3”LaBr$_3$ crystals.](image)

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As for the NaI crystal, it turned out to be ineffective when working close to neutron the generator for it has too many signal overlaps due to its large size low photopeak-to-Compton ratio. Examples of spectra obtained by the NNA-based device with γ-ray detectors based on BGO and LaBr₃ crystals of the same size are shown on Figure 1.

Three neutron detectors based on 7×7×21cm³ plastic scintillator have been equipped with the same electronics as gamma-detectors, so that they can be plugged into standard gamma-modules of the DAQ.

2.1.3 Data acquisition system

A specialized data acquisition system (DAQ) developed for NNA devices analyzes coincidences between the alpha-detector and detectors of γ-rays, and transfers the filtered coincidence information to the analyzing computer.

The DAQ has two key elements: a universal spectrometer performing digital signal processing from γ-ray and neutron detectors, and a coincidence module that correlates the data from spectrometers with information coming from detectors of associated α-particles. Spectrometer board is built inside each detector close to the divider of the photo multiplier tube, and is connected to the coincidence module by a single 4 twisted-pairs cable.

![Figure 2. Left: compact DAQ board for servicing up to four γ/neutron detectors and one α-particle detector. Right: DAQ for servicing up to 40 α/γ/neutron detectors in any combination.](image)

Coincidence module was developed in two form-factors. The first is a compact DAQ intended for small NNA-based devices with up to four γ-ray or neutron detectors (see left
photo on Figure 2). It is based on a programmable logic device (PLD) installed on a printed board right on top of the board with preamplifiers servicing associated α-particle detector.

The second type of the DAQ (see right photo on Figure 2) is located in a single 2U-high 19”-wide crate and can service up to 40 α/γ/neutron detectors in any combination.

Both types of DAQ contain power supplies and controllers, and can operate each of the connected detectors via a single cable. The fact that operation of the DAQ can be reprogrammed in the respective PLDs allows us to include different detection modes, such as multiple coincidences between neutron detectors that are needed to detect shielded fissile materials, or obtaining time-of-flight spectra from radiographic applications.

2.1.4 Assembling the device for inspection of containers

The scanning module has been assembled using standard crates in a standard 19” rack. The geometry can be easily changed to investigate different geometries (Figure 3). The scanning module can be used both in one-side access geometries and in two-side access geometries.

![Figure 3. Base module frame based on standard 19” rack.](image)

2.2 SOFTWARE

2.2.1 Modeling with MCNP

A full MCNP model of all components of the NNA devices has been created. This model is used to optimize the device’s geometry by providing counting rates for all detectors, estimating particle attenuation and scattering, etc.
2.2.2  \textit{Low-level DAQ software}

The low-level DAQ software controls the measurement process, including neutron generator control, high voltage and signal processing parameters of all detectors, coincidence analysis, data taking and storage. All the detector’s settings are stored in the energy-independent memory on their respective spectrometers, and these settings are automatically taken by the program as defaults on startup. Thus, there is no need in a separate DAQ configuration file. The user may change the settings if needed, rewriting them in the spectrometer’s memory.

The neutron generator is controlled using UDP protocol either automatically or manually. In the automatic mode the neutron generator is switched on when a new measurement starts, and is switched off when it ends. In the manual mode the operator can control the state of the neutron generator independently of any measurements.

2.2.3  \textit{Calibrations and spectral regression}

The Calibration program module transforms the event-by-event data obtained from DAQ into energy spectra of gamma-rays for each “voxel” of the inspected volume. To do that the following operations are performed:

1. Non-linear energy calibration for each gamma-detector is determined from the total energy histogram obtained from the corresponding gamma-module.

2. A time-to-distance calibration for each pair of gamma-detector – alpha-pixel is applied to the event-by-event data, transforming the TOF channels into depth coordinate in centimeters.

3. Energy calibration is applied to the event-by-event data to obtain $\gamma$-ray energy in keV.

4. The data are integrated over depth coordinate using Gaussian smoothing, and the result is stored in energy spectra with the selected range and energy bin.

5. A correction for geometrical efficiency is applied to the energy spectra of $\gamma$-rays.

The calibration module also includes the description of the measurement geometry (types, dimensions, and positions of the $\alpha$-particle- and $\gamma$-ray detectors), which allows it to perform non-linear time-to-distance calibrations, and to calculate geometrical efficiency.
Spectral regression is done by Partial Least Squares (PLS) method. PLS is a stable method that can handle low statistics and large number of fitting components. At present the experimental data are fitted with about 30 components that are experimentally measured responses of the device to Li, B, C, N, O, F, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Br, Cd, Sn, and Pb, as well as some additional components (e.g. 511 keV annihilation line). Response functions were measured for all two types of gamma-detectors: BGO and LaBr₃ (Figure 4).

![Figure 4. Response functions for BGO-based and LaBr₃-based detectors.](image)

### 2.2.4 Automatic decision-making software

The software module based on «fuzzy» logic automatically analyzes the concentrations of chemical elements obtained from the regression procedure, and produces the decision about whether the given “voxel” contains hazardous material or not. The results are visualized either as 3D spatial distribution of the chemical element of interest, or as a 3D distribution of hazardous substances (Figure 5).
A possibility of joining adjacent 3D “voxels” has been added to the data analysis system in order to improve the spectral statistics. The “voxels” may be joined either if the energy spectra of gamma-rays in them are similar (the degree of the required “similarity” is a parameter), or if they are located at the same distance (depth) from the NG target. Both approached allow one to combine information from a single large object that is split between several “voxels”. Which one will be used in practice will be determined after the real experimental data from the scanning module will be available.

2.3 TEST MEASUREMENTS

A number of test measurements have been carried out:

1. detection of explosives’ simulants in suitcases with portable SENNA devices;

2. inspection of large objects with container scanning modules;

3. obtaining radiographic images of large objects using two side access geometry;

4. Identification of liquids in sealed containers;

5. Identification of hazardous chemicals in metallic shells.
3 CONCLUSIONS

The hardware and software developed as the result of this Project can be used to assemble devices based on Nanosecond Neutron Analysis (NNA) technique to detect explosives and other threat materials in different scenarios: in suspicious unattended objects and luggage, in cargo containers, in unexploded ordnance, etc.

The chosen approach allows one to build both very compact and light systems, and very large automatic systems for detection of a wide variety of threat materials from the same basic modules: AP neutron generators with associated particle detectors with different pixelization, \(\gamma\)-ray/neutron detectors with on-board digital spectrometers, coincidence modules, and data analysis software.

4 LIST OF PUBLICATION AND CONFERENCE REPORTS
