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Neutron-based methods for the detection of explosives

Introduction

Neutron radiation is able to penetrate through some heavy metals, such as metallic materials. It also significantly interacts with some light, organic materials. Therefore, it can be directly used for the detection of explosives, as well as other materials. Nevertheless, these methods are not frequently used in security practice and they are not used at all in the Czech Republic. Determining suitability of use in individual security situations is firstly subject to a full understanding of the relatively complex physical principles of neutron methods. Neutron methods are often mistakenly expected to be used in the security controls of objects of the first degree. Here they cannot compete with other systems, especially X-rays. However, there are many possible security situations where the security controls of first and second degree clearly indicate that the information obtained for assessment of an object controlled is not sufficient; the only possible method for the next (higher) degree is some of the neutron-based methods.

In neutron-based methods, checked baggage is irradiated by a neutron flow (flux), also called "neutron radiation". Then, either scattered neutrons or better gamma radiation from the controlled material that was activated by falling neutrons are detected. It is worth noting that neutron detection methods for explosives during safety inspections are generally inappropriate to be considered as a proper term for neutron activation analysis. The term "neutron activation analysis" (NAA) is used for a particular instrumental method, where a sample is firstly exposed to the neutron flux from the nuclear reactor; then it is removed and gamma radiation is measured after a certain time delay (up to about half an hour). Therefore, it is better to use the term "neutron-in, gamma-out".

Together with the detection of explosives, the methods of "neutrons in – gamma out" are used for detecting drugs, chemical or biological warfare substances and also for searching for various smuggled goods, such as different types of food, chemicals, etc. This process is carried out in customs clearance procedures, where the customs officers compare the chemical composition of transported substances with the declared content. It is also necessary to note that neutron radiation cannot be used to check human persons because it is harmful to living organisms. Regarding the basic principles of radiation protection, any ionizing radiation must not be used to check persons unless the requirement for justification is met. However, there is no harmful contamination of irradiated material, including food and beverages.

Detection of slow neutrons

(Neutron backscattering)

These devices consist of a source of fast neutrons and a slow neutron detector. The source (radionuclide or neutron generator) and detector are directed towards the area under investigation. The source is shielded in the direction of the other sides, especially towards the detector. The area under investigation is irradiated by a stream of fast neutrons (with energy greater than about 1 MeV) from the source. This radiation is very pervasive, especially through metallic materials, etc. They do not react with the electron encasement of neutrons. In the case of neutrons colliding with the nucleus of an atom of the object under investigation, there is elastic scattering; the principle of conservation of momentum is applicable for this: the mass of the nucleus of the overwhelming majority of atoms is substantially greater than the mass of the neutron; therefore the neutron provides the nucleus with only a tiny fraction of its kinetic energy, in central collision. However, when the neutron collides centrally with the nucleus of the atom (with the proton) of hydrogen (A=1), it passes a more significant part of its kinetic energy. If, therefore, there is a substance with a high hydrogen content in the area under investigation, rapid neutrons are quickly decelerated to slow speeds by multiple collisions with these hydrogen atoms (their energy is reduced to a much smaller amount (less than 10 keV) in which they are thermally balanced with the environment; they are slowed down (slang: “thermalized”). This results in the neutron cloud near the sensor head containing a number of slow neutrons, some of which will be captured by the detector. Nowadays, the types of neutron detectors are sensitive to slow neutrons and insensitive to fast neutrons. The signal may not only be caused by explosives or drugs, but all substances with a higher content of hydrogen, such as water, petrol, oil, paraffin, etc.[1]

This principle was used decades ago. For example, the SNB (the National Security Corps) pyrotechnics had a handheld explosive detector HED available before 1989[2] – L3A1 type explosive detector.[3] For better insights into the basic principles of detecting explosives by detecting slow neutrons, and for better insights into the benefits of more modern methods, it is necessary to take a closer look at this historical tool.

Fig. 1: The detector of explosives HED L3A1, the first and most recent neutron detector of explosives used in the Czech and Slovak Republic[4]

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[1] For example, use of this method against a soil background with a moisture content greater than 15% is impossible.
[2] Excluded from the inventory of the Ministry of the Interior of the Slovak Republic in 1993.
[3] Supplied by British S&D Security (Equipment).
[4] Author’s archive.

The appliance was designed to detect hidden materials, such as explosives, drugs and other smuggled goods with a higher content of hydrogen atoms, in the doors of cars, their thresholds, in the walls of transport containers and superstructures of trucks, in walls, floors and ceilings and other inaccessible spaces. The appliance consisted of a handheld probe with a telescopic handle, an electronic evaluation unit attached to the belt, a connection cable and a headset. The sensor head contained a small radioactive source (radioisotope) of fast neutrons located in a polyethylene block at the centre of the toroid filled with gas of the detection chamber sensitive to slow neutrons. The detected slow neutron caused an increase in the electric current: a pulse that was registered by a pulse counter. The resulting signalling of the hand gauge or headset was derived from the number of pulses per unit of time. When checking ("scanning") a given area, the signal size was roughly constant; it significantly changed only in the places with the material containing a higher content of hydrogen. At the end of the test, the probe was placed in a case with a polythene shield intended for the probe head. Even during operation, the head of the probe had to be at least 30 cm away from any part of the human body. The amount required to detect was 100 g of ammonium nitrate in contact with the head, 1 kg of ammonium nitrate at a distance of 3 cm.

Detection of retro-scattered neutrons is problematic for a large number of false alarms. Pyrotechnics complained that each larger volume of oil or vaseline was causing a signal. The signal may not only be caused by explosives or drugs, but all substances with a higher content of hydrogen, such as water, petrol, oil, paraffin, etc. Regarding open appliances, there is a problem with the health protection and safety of personnel. Nowadays, pocket gamma detectors which detect backward-scattered gamma radiation (Compton scattering) are used as small handheld devices for this type of vehicle inspection.

"Neutron-in, Gamma-out" Methods

The methods of "neutron-in, gamma-out" are used as a very promising group of techniques. It is generally accepted for all of these methods that different chemical elements in the material of the object controlled produce gamma radiation with varying wavelengths characteristic of these individual elements after scattering or absorption of the falling neutrons. Probability of these reactions depends on the microscopic effective cross-section for the radiation capture, which depends on the number of protons and neutrons in the nucleus and on the energy of the falling neutrons. By distributing the measured gamma ray spectrum into contributions from individual chemical elements, we can obtain an elementary composition of the material, a mutual ratio of representation of the individual elements, the so-called stoichiometric formula of the substance; thus we can determine the type of an explosive.

	N (weight in %)	O (weight in %)	C (weight in %)	H (weight in %)
Explosive C-4	30.26	41.71	24.35	3.68
Pl SE M	29.88	39.73	26.38	4.01

Table 1: Example of stoichiometric formulas of American plastic explosive of type C-4 and Czech plate explosive PL SE M (Plastic SheetExplosive Military)[1]

The main advantage of this group of methods is their high penetration capability. The smuggled goods may be detected even if they are hidden in a steel container or behind concrete, metal or other walls. These devices are therefore suitable for searching explosives, like those in the design with a chamber, but also for searching for chemical warfare substances, anthrax, etc. in the hand luggage of visitors in the object. Large portal-type designs are suitable for checking vehicles at the entrance to the building; however, they are used very rarely for these purposes. The large portal-type designs are mostly used for customs inspections. Portable designs are suitable for security inspections in buildings, especially in the search for more powerful explosive systems hidden behind walls, ceilings or under floors. Mobile versions in vans are suitable for searching for more powerful explosives in vehicles parked in close proximity to a protected building.

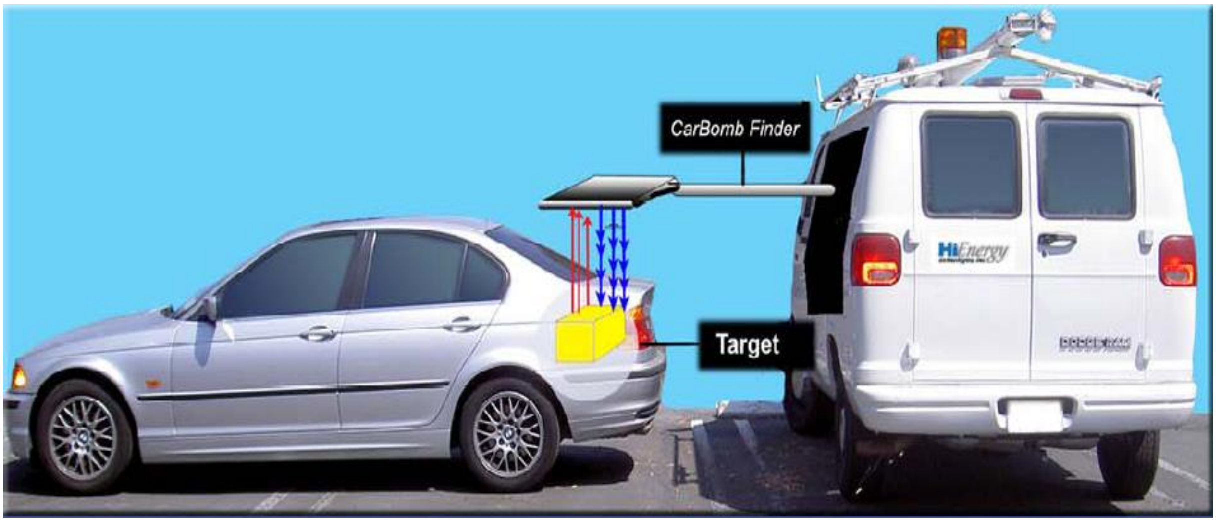

Fig. 2: Vision of detector "CarBomb Finder 3C4". The explosive can be detected within 11 seconds; the exact stoichiometric formula will be released within 30 seconds. Operator shielding is a combination of metal / water.[2]

Prompt Gamma Neutron Activation Analysis

Prompt gamma neutron activation analysis was the first method of the group called "neutron-in, gamma-out", whose principle was used to develop the prototypes

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[1] TUREČEK, Jaroslav, Bryan SCHVITTER, David MILJAK and Miroslav STANCL. NQR Characteristics of an RDX Plastic Explosives Simulant. *Applied Magnetic Resonance.* Wien: Springer, 2012, pp. 1-11, ISSN 0937-9347. URL: http://dx.doi.org/10.1007/s00723-012-0337-6, DOI: 10.1007/s00723-012-0337-6, 63%

[2] It was first introduced by HiEnergy Technololgies, Inc. In 2005, it was offered by Clear Path Technologies, LLC, http://www.officer.com/product/10043658/hienergy-technologies-inc-carbomb-finder-model-3c4

of devices for the detection of the explosives for security purposes, specifically for the detection of explosives in checked baggage at airports. For a better understanding of the basic principles of the “neutron-in, gamma-out” and for a better understanding of the progress of more advanced methods, it is necessary to take a closer look at one prototype of the two prototypes built in the past: namely the Czechoslovak prototype.

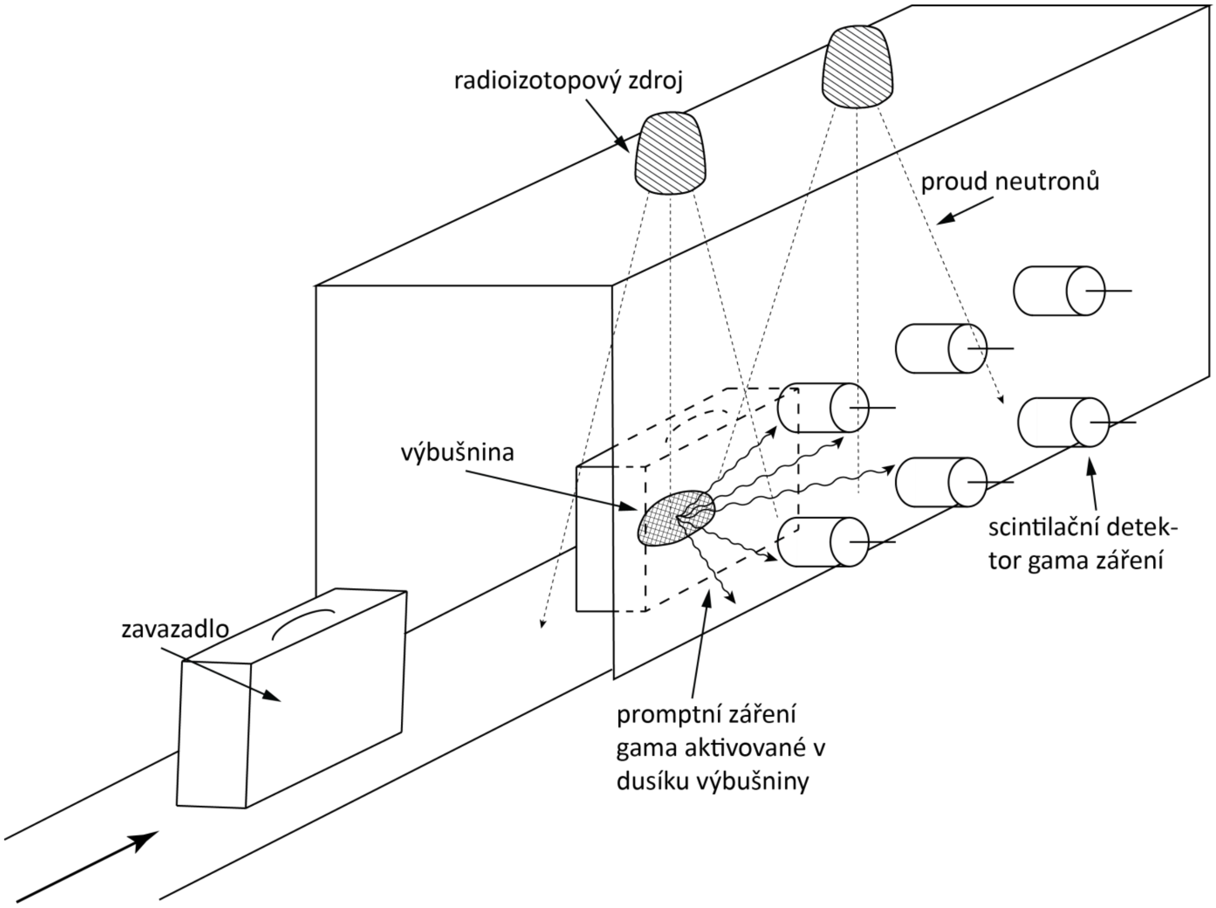
The inability to reliably detect pentrite- or hexogen-based plastic explosives was clearly indicated on Christmas day, 1988, when Islamic Lybie agents (probably) used Czechoslovak Semtex 1H to bring down PanAM flight 103 (Boeing 747), causing it to crash into the town of Lockerbie. This triggered a wave of research and development projects to detect explosives in luggage. The methods of “neutron-in, gamma-out” were very promising. In the United States, the Californian company, Gamma-Metrics (included in Thermo Instrument Systems Inc.), was developing the device upon the principles; journalists wrote about a “silver bullet”. It is less known that a similar device was being developed simultaneously and independently in Czechoslovakia. Based on the proposal of the Institute of Nuclear Physics in Řež, the company, Tesla Přemyšlení, began to produce the prototype. The appliance was based on the Prompt Gamma Neutron Activation analysis - PGNA. Often the more specific and more general term TNA (Thermal Neutron Analysis) is used - see the following chapter.

In this method, the detector bombards the object under investigation with low-energy neutrons. Between the neutrons and nitrogen there is nuclear reaction generating gamma-radiation of a characteristic wavelength. If the device detects this gamma-radiation, it will trigger the alarm. In these detectors, the object under investigation is exposed to a flow of thermal neutrons, e.g. the neutrons whose kinetic energy is relatively low (0.025 eV at room temperature) because it is thermally balanced with the environment. These neutrons cause a nuclear reaction on the elements of the object under investigation - the so-called neutron radiation capture. The thermal neutron is captured by the nucleus. Therefore, the proton number of the nucleus remains the same, but the number of neutrons and thus the relative atomic mass is increased by one. Excessive energy is released by emission of the so-called prompt gamma radiation, which occurs immediately. The value of energy of quantum of gamma radiation depends on the type of the element. Nitrogen, which is contained in the explosives at least in 25 %, emits the quantum with very high energy (11 MeV), which is, by the way, one of the highest values observed in these reactions. The average diameter is 5-6 MeV. As a result, nitrogen peaks in the overall energy spectrum are easily distinguishable; presence of gamma radiation with quantum energy 11 MeV reliably shows presence of nitrogen. The size of the signal can be used to determine the quantity in case of experimental arrangement. The amount of atmospheric nitrogen in the controlled area is negligible due to its relatively small spatial density. Size of the signal does not depend on chemical bonding at all. The effective cross-section decreases with increasing neutron energy. Therefore neutrons with very low energy - thermal neutrons - are used.

As the sources of neutron radiation, we can use neutron generators or radioisotope sources. Radioisotope sources use the reaction (α,n). Depending on individual sources of radiation α, various neutron sources are referred to as Am Be source, Ra Be, Po Be or $^{252}Cf^{*}$. Deuterons are accelerated by a strong electrical field in the neutron generators ^{2}H (their ions), whilst bombarding the target, nuclei of heavy hydrogen, tricium $^{3}H^{*}$; it results in the production of neutrons with the energy of 14 MeV. The lifetime of these resources is long, mainly due to the lifetime of the target. The artificial radioactive isotope of californium $^{252}Cf^{*}$ can be used as the radioisotope source; it can intensely and spontaneously cleave (half-life: 2.6 years) together with the release of 2–3 fast neutrons with a mean energy of 2 MeV.

Neutrons emitted by these sources have different energy values, which need to be reduced before reacting with nitrogen. This is accomplished by moderating (slowing) the motion where a moderator is placed between the source and the irradiated object - e.g. a layer of material with a high content of hydrogen, such as paraffin, water, etc. Neutrons gradually lose their kinetic energy by colliding with the nuclei of the moderator material on their journey through the moderator. This will continue until their kinetic energy is thermally aligned with the environment and also aligned with the thermal vibrations of the atoms of the moderator substance. The kinetic energy of neutrons is effectively transferred to the nuclei of hydrogen due to the comparable mass of the hydrogen and neutron nuclei. In practice, however, it was shown that the own material of the object under inspection was best to be used as the moderator.

Scintillation or semiconductor detectors can be used for detection. In scintillation detectors, the particles of the scintillator substance absorb gamma radiation and their electrons are transferred into an excited state. When these electrons return to their original state, the released energy is emitted in the form of light in the visible or ultraviolet area. Intensity of these scintillations is proportional to gamma radiation. The flow of light photons is amplified by a special tube - the photomultiplier. The electrical signal from the photomultiplier is led into the multichannel analyser, where we can see the energy spectrum right on the screen. In the case of semiconductor detectors, the radiation is directly produced by the pair of electron-holes in the non-conducting area (depleted layer) of the semiconductor P-N transition in the reverse direction.



radioizotopový zdroj	radioisotope source
proud neutronů	flow of neutrons
výbušnina	explosive
zavazadlo	luggage
promptní záření	prompt gamma radiation activated in the nitrogen of the explosive
scintilační detektor	scintillation detector of the gamma radiation

Fig. 3: Scheme of the incomplete prototype of the detector of explosives from Tesla Přemyšlení (turn of the 1980s and 1990s) using the prompt neutron activation analysis according to the proposal of the Institute of Nuclear Physics of the ČSAV (Czech and Slovak Academy of Sciences) in Řež.[1]

In the prototype from Tesla Přemyšlení, the objects under investigation (luggage) were arriving at the measuring tunnel via the conveyor belt. The radioisotope sources of neutrons $^{252}Cf^{*}$ were located at the top. Because they are the sources of neutrons and also the sources of very pervasive gamma radiation, the whole tunnel had to be perfectly shielded from all directions, which meant that the total weight of the device was growing considerably (tens of tonnes). From both sides of the tunnel there were a large number of scintillation monocrystalline NaI gamma-radiation detectors. Detectors had to be shielded from gamma radiation and neutrons right from the

[1] The author on the basis of description of prof. Ing. V. Hnatowicz, DrSc. in the 90s.

sources. Larger quantities were more advantageous for higher efficiency of detection; moreover, the comparison of the mutual rates of intensity of the signals from individual detectors indicated the location of the explosive in the object. In fact, the device from Tesla Přemyšlení was able to find about 300 g of plastic explosives in a variety of luggage in just a few minutes (the value of Gamma-Metrics detectors was about 1 lb, e.g. 0.45 kg). If a low alarm threshold were to be set, the false alarm could be triggered by unharmful items with a high content of nitrogen, such as some larger boots or cheese rounds; because the size of the signal depends on the amount of nitrogen atoms and not on its chemical bond. The advantage would be that detection was not dependent on the position and arrangement of the explosive in the luggage and practically not even shielded by metals! The radioactivity of checked luggage did not exceed the values of natural radioactivity. The contents of the luggage would therefore remain completely undamaged. But this detector would be very heavy, expensive and slow. However, the main reason for not installing the most advanced detection methods for explosives is that "civil airports operate as long-term profitable companies"[1] and invest in security measures only if it is required by law; preventive security beyond the statutory duty is not a necessity for them. In addition to the explosives mentioned above, most substances would be detectable by the prompt neutron activation analysis.

Thermal Neutron Analysis – TNA

The analysis with slow neutrons consists of irradiating a controlled object (e.g. a piece of luggage) with slow neutrons, followed by detection of gamma radiation as a product of capture of neutron by the nucleus of hydrogen or nitrogen contained in the explosive. The main drawbacks of thermal neutron analysis include the time duration of measurement (up to minutes), inability to detect oxygen or hydrogen, and thus a high number of false alarms resulting therefrom.

Fig. 4: Checking a case with the TNA method, using the appliance of SPEDS from the company called Ancore.[2]

[1] ŠČUREK, R. MARŠÁLEK, D. KONEČNÝ, M. STONIŠ, O. Airport Emergency Plan and Emergency Events Management System in transport of Renewable Resources. In: *Advanced Materials Research.* Switzerland: Trans Tech Publications, Vol. 1001, pp. 441–446, 2014, ISSN: 1662-8985, doi:10.4028/www.scientific.net/AMR.1001.441

[2] www.rapiscansystems.com

The compact system, SPEDS (Small Parcel Explosive Detection System), of the company called Ancore (included in the Rapiscan Systems) is a good example thereof (able to pass through a standard door with a thickness of 90 cm).[1] This system is designed to search small hand luggage either as separated device or rather as part of an X-ray system, etc. Its advantages are obvious in the automatic detection of tubular bombs, liquid explosives, plastic explosives hidden between metal tools, as well as in the search for explosives in electronics, such as laptops, cameras, etc.

Another example is the system of VEDS (Vehicle Explosive Detection System), also from Rapiscan Systems, which has the isotope (^{252}Cf) neutron source designed for vehicle and container inspection (stationary and mobile versions). This system detects nitrogen contained in the explosives.

Fast Neutron Analysis – FNA

The Fast Neutron Analysis operates by irradiating a controlled object (e.g. a piece of luggage) with fast neutrons, followed by detection of gamma radiation as a product of non-flexible scattering of neutrons on the nuclei of light elements (carbon, nitrogen, oxygen, etc). Therefore, the energy of neutrons must be greater than the threshold value given for each detected element (approximately 5 MeV for carbon). The wavelength arrangement and the corresponding secondary gamma radiation intensity produced by reactions characteristic for the detected elements then indicate the relative concentrations of the elements in the space controlled. The disadvantage of this method is the inability to reproduce the spatial structure of the object controlled and also the low rate of signal-to-noise, resulting in long detection times.

The combination of TNA and FNA is used by the above-mentioned VEDS system in the version with the electronic generator of neutrons. It is a better method and more advantageous in terms of safety regulations. However, it is also noticeably more expensive.

Fig. 5: Customs inspection done by a combination of methods TNA and FNA – system VEDS (Vehicle Explosive Detection System).[2]

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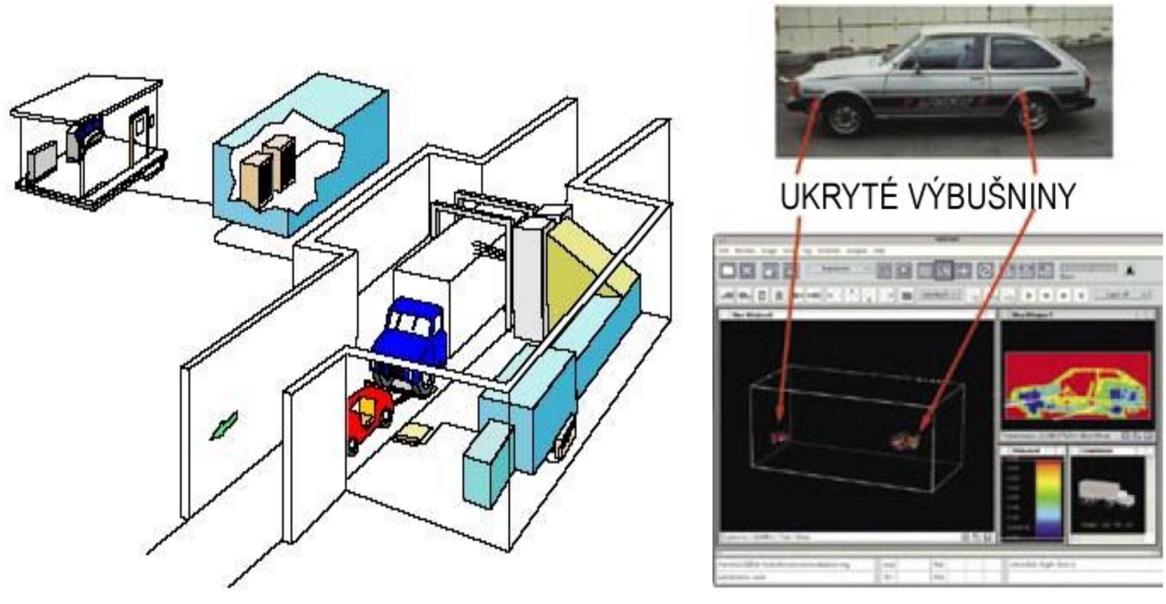
[1] www.rapiscansystems.com
[2] Rapiscan Systems http://ru.uasm.org/activity/products/3/1-1/1/4/nejtronnaasistemadosmotradlakontrolatransportnyhsredstvrapiscanvedstmgantry

Pulsed Fast Neutron Analysis – PFNA

The Pulsed Fast Neutron Analysis operates by in irradiating a controlled object (e.g. a piece of luggage) with fast neutrons in a fixed time gap (according to - for instance - pulsed operation of the neutron source), followed by detection of gamma radiation as a product of non-flexible spread of neutrons on the nuclei of light elements (carbon, nitrogen, oxygen, etc). Pulse operation allows time information to be used (time conformance or nonconformance of measurement) to activate gamma detectors only during short intervals according to neutron source timing. This can be very useful for reducing unwanted backgrounds.

By using information of the flight time of neutron (TOF - Time-of-Flight), we can determine the position of material detected inside the volume controlled, because both the neutron velocity and gamma radiation velocity are basically known. The starting signal for the gamma radiation measurement is determined by each neutron pulse; the end signal is determined by the gamma detector itself (gamma rays are moving at the speed of light; much faster than the neutrons). If this is, for example, combined with vertical scanning of an object controlled using a neutron beam while simultaneously moving the object in the direction perpendicular to the scanning plane, the pulses provide a three dimensional spatial display capability of the object under inspection. The ability to distinguish is then given in spatial elements called voxels.[1] The type of material is again determined by spectroscopy of gamma radiation detected.



ukryté výbušniny	hidden explosives

Fig. 6: Example of the arrangement of automatic detection of the explosives by the method PFNA and the spatial display of explosives hidden in a car. This is the system of ACI (Ancore Cargo Inspector), the most expensive scanner of all time, designed for security screening.[2]

[1] Alternatively, there are pixels known for flat images.

[2] materials supplied by Ancore, e.g. the company currently included in Rapiscan Systems; www.rapiscansystems.com

PFNA is the only technology which provides a full determination of material types in objects inspected, ranging from small hand luggage to large marine containers. Similar imaging capabilities are present in X-ray computed tomography or magnetic resonance imaging. However, these technologies are only applicable for smaller objects and provide much less information than PFNA.

The disadvantage of PFNA systems is that they are very large and expensive. This is because they require large accelerators of particles for the nanosecond neutron pulse mode. These systems are also slower due to the more complicated scanning method, specifically for the vertical sweep of the neutron beam and horizontal motion of the object, with simultaneous measurement of TOF in individual neutron pulses. They are able to find an explosive weighing several tens of kilograms in the cargo container in about 10 minutes. An example of a manufacturer of security scanners using this principle is the company called Ancore in the group of Rapiscan Systems.[1]

Pulsed Fast/Thermal Neutron Analysis – PFTNA

PFTNA is a combination of the PFNA and TNA technologies described above. In a typical arrangement, the neutron generator produces fast-neutron pulses with a microsecond width (neutrons with 14 MeV energy in pulses shorter than 10 μs). During these pulses and eventually also shortly after, the prompt gamma radiation is measured, e.g. the radiation generated as a result of the reactions of non-flexible scattering of neutrons on the nuclei of elements for the purposes of detection of carbon and oxygen. Then, the neutron flow from the generator is interrupted for about 100 μs. During this interval, the neutrons are thermalised and the prompt gamma radiation is measured, e.g. the radiation generated in reactions of neutron capture for nitrogen and hydrogen detection. The cycle is then repeated again. The advantage and disadvantage of using the pulse source is that the signal/noise ratio gets improved, but the overall signal capacity is reduced by the pulse mode, requiring a much higher neutron peak intensity. This can, in turn, make the measurement of the spectrum very difficult during the pulse. The disadvantage of the principle is, therefore, the impossibility to display a spatial arrangement of materials and the low ratio of signal/noise due to the minimum possible neutron pulse width (microseconds instead of nanoseconds) of the portable neutron generator.

[1] www.rapiscansystems.com

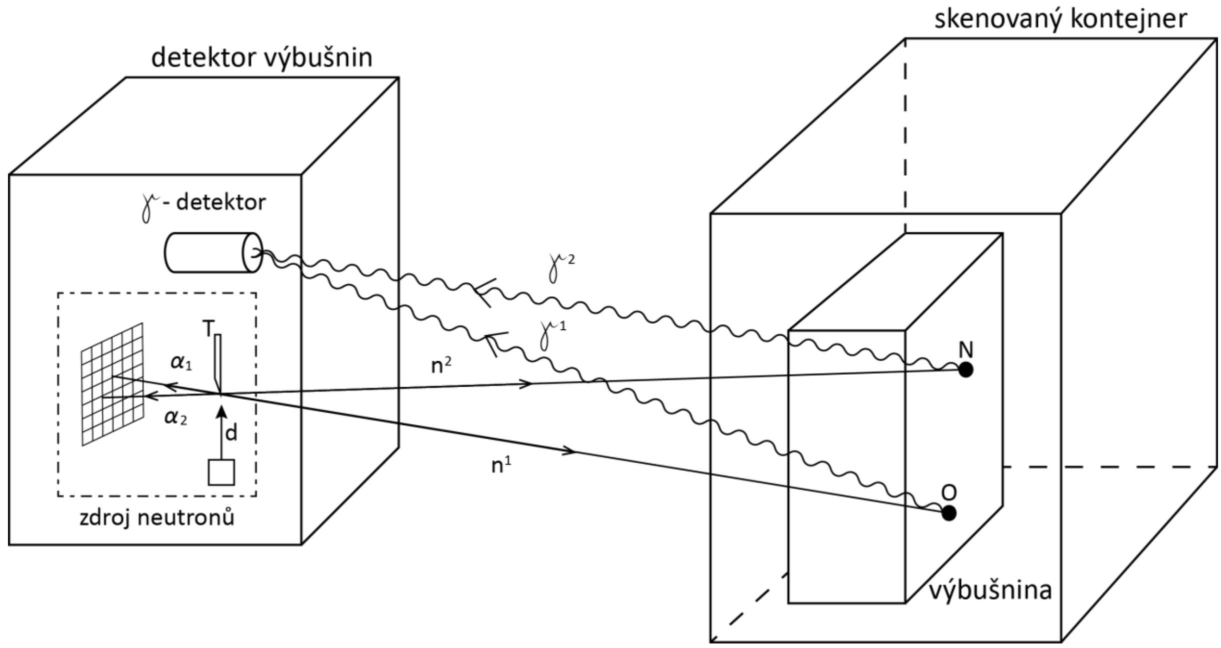
Fig. 7: An example of the portable explosive and drug detector working on the principle of PFTNA is PELAN IV (Portable Elementary Analysis with Neutrons) developed at the University of West Kentucky.[1]

Method of Associated Particle Imaging

(API – Associated Particle Imaging; AP; APSTNG – Associated Particle Sealed Tube Neutron Generator)

The method of displaying associated particles is a PFTNA variant which additionally involves the detection of associated alpha particles produced in the neutron generator.

[1] http://ipsmktg.com/pelan_iv.htm



detektor výbušnin	detector of explosives
skenovaný kontejner	container scanned
zdroj neutronů	source of neutrons
výbušnina	explosive

A – matrix of detectors of associated α

D – deuteron

T – target

n1 – the neutron generated at time T1

α1 – associated – particle generated at time T1

O – atom of oxygen in the explosive with which neutron n1 collided

N – atom of nitrogen in the explosive with which neutron n2 collided

γ1 – γ photon generated by collision of neutron n1 with oxygen atom O; its energy corresponds to collision with an oxygen atom

γ2 – γ photon generated by collision of neutron n2 with nitrogen atom N; its energy corresponds to collision with an nitrogen atom

Fig. 8: Scheme of PFTNA (or NNA) with detection of associated API particles.[1]

This method uses the characteristics of the reaction between deuterium and tritium (D-T) in the generator; the sources, together with each fast neutron (14 MeV), emit one low-energy alpha-particle (about 3 MeV) under the angle of approx. 180° (in the reverse direction). Within the modified forms of the D-T generators, these alpha particles can be registered using the detectors able to determine the point of impact. The method registers both the moment when the alpha particle is generated (and hence the accompanying neutron), as well as the relative direction towards the source (and hence the direction of the accompanying neutron as its direction of motion is

[1] Author

opposite to the direction of motion of the alpha particle). Such fast neutrons produced in this way are therefore also called “tagged”; by associated particles), in both the time and the direction, which can lead to significant reduction in background signal. This is again the technology of TOF (Time-of-Flight) as described in the section of PFNA. This makes it possible to determine the distance travelled by the neutron before the collision. Since the neutron flight direction is also known, this method can, in principle, provide spatial, three-dimensional viewing, without the need for scanning (as in PFNA). The type of material in the voxel (volume element) of the space under inspection is again determined using the gamma spectroscopy. Thus, the method of displaying the associated particles is capable of providing a three-dimensional view of the chemical composition of the object inspected, voxel by voxel.

It should be noted, however, that with respect to the use of the alpha detector, the API devices tend to have too low a flow of neutrons (to avoid random time coincidence), which prolongs the measurement time. Some neutrons also lose some of their initial energy in collisions with surrounding substances and they are no longer monochromatic, which limits the spatial resolution of the method.

Nanosecond Neutron Analysis – NNA

The nanosecond neutron analysis is the latest attempt at improving the technologies of PFTNA and API to use nanosecond time information to create a three-dimensional layout view of elements in an object inspected. The NNA analysis is based on the irradiation of an object under inspection by fast neutrons and the detection of gamma secondary gamma radiation in a narrow time gap (nanosecond) measured in relation to the associated particle (either a fragment of fission in case of an isotope as a neutron source or an alpha particle in case of a D-T neutron generator).

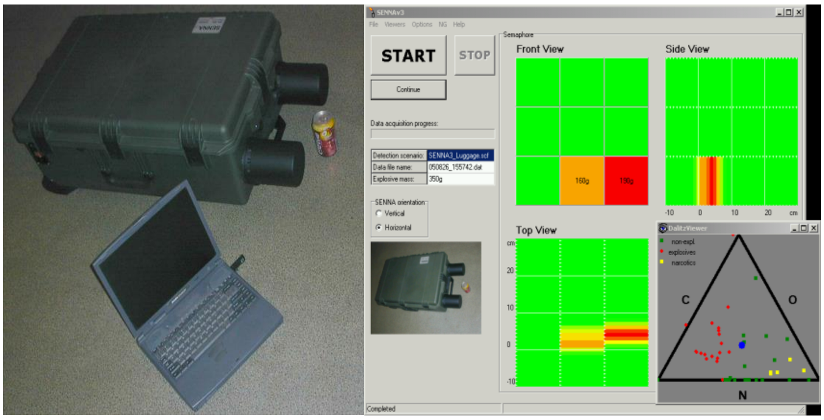


Fig. 9: Demonstration of liquid explosive detection by the prototype portable device "SENNA" – NNA with spatial view.[1]

When an associated particle detector is applied, which is sensitive to the point of impact, the NNA analysis provides a three-dimensional view of the element layout in the object inspected. The impact-sensitive detector of the associated particles allows the possibility to obtain a “flat” image, while the nanosecond timing provides an image of its “depth”. This makes it possible to detect a small amount of explosives hidden amidst a massive amount of the explosives.

[1] Author and VAKHTIN D., KUZNETSOV, A., V. G. Khlopin Radium Institute, St. Petersburg.

Results

Neutron methods are generally irreplaceable for the volume detection of hazardous substances contained in metal containers. Luggage containers with thicker metal walls mean a serious problem for all x-ray systems for luggage check-in at airports. X-rays commonly mark them as a suspect; however, the thicker layer of metal usually prevents determination of the type of organic material hidden behind this layer, or it even entirely prevents the detection of presence of some organic material. This applies to dual-energy X-ray methods, computer tomography and diffraction. Nuclear quadrupole resonance or nuclear magnetic resonance cannot, of course, measure material inside a metal container. The metal container is also an ideal solution for the hermetic isolation of contents at the technological level of the ultra-high vacuum, which reliably prevents the detection of trace particles by devices or dogs. Advanced neutron technologies with spatial imaging and spectroscopy in each elementary volume of the space inspected, such as PFNA or NNA with API, are capable of recognising explosives or hazardous chemical and biological substances in both a thick-walled container and those surrounded by other, harmless organic materials. Since this is a volumetric method of detecting explosives, these methods are also able to reliably exclude the presence of a larger,[1] airplane-threatening, amount of an explosive. Therefore, the neutron methods for luggage security checks at airports are irreplaceable; if we require a higher degree of security, neutron methods are necessary. The main disadvantage of neutron methods is that they are relatively slow. Therefore, the neutron methods of detecting explosives should have an irreplaceable position in the security inspections of higher degrees (second and third). When applied to the third and higher level, the number of luggage pieces under inspection would be more likely in permilles of their number at the first level. This significantly inhibits the negative properties of these neutron methods - slow analysis and higher price.

A portable device based on NNI with API should not be missing even in the top **pyrotechnic teams**, due to the possibility of volume **analysis of the organic contents of thick wall containers**. In the case of an uncertain result of X-ray imaging and trace particle sampling, this neutron method should be used either to reliably eliminate the presence of a larger and more dangerous amount of the explosive, even in surface contamination of the container by the explosive, or it detects vice versa the presence of higher amount of the explosive. In case of positive detection, the operator will also have information about the type of the explosive, its total amount and its spatial arrangement in the object inspected. If the terrorists use a **combination of NVS and chemical or biological warfare substances**, the NNA with API is irreplaceable for the inspection of thick-walled containers. In addition to the explosive, it excludes or detects the presence of a certain amount of these hazardous substances, including the image of their spatial location and determination of their stoichiometric formula. This capability could be used, in addition to the NVS, for the detection and analysis of old chemical ammunition, such as that used in World War I. The NNA with API is irreplaceable for pyrotechnic teams even if the **NVS is buried, walled or concreted,** and can be accessed only on one side. For the optical “stand-off” methods, such as

[1] Accurate information cannot be given (EU Restricted). Due to inappropriateness, the possibilities of technical masking of the explosives before their positive detection by the existing methods during luggage security checks are not precisely specified.

millimetre or terahertz wave imaging or Raman spectroscopy, these obstacles are absolutely impenetrable. The only X-ray stand-off imaging method is the method of Compton scattering. However, this method is not capable of distinguishing explosives from harmless organic substances.

Conclusion

From the point of view of safety, the methods of "neutron-in, gamma-out" are suitable for higher degrees of luggage security checks at airports in cases where luggage is in containers with stronger metallic walls. For pyrotechnic teams, the methods of "neutron-in, gamma-out" are suitable for volume detection, spatial imaging and type analysis of explosives and hazardous chemical and biological substances in thick-walled metal vessels, as well as for volume detection, spatial imaging and type analysis of explosives in buried, concreted or welded improvised explosive devices (IED), which may only be accessed from one side.

List of Abbreviations

ACI – Ancore Cargo Inspector

API – Associated Particle Imaging

APSTNG – Associated Particle Sealed Tube Neutron Generator

FNA – Fast Neutron Analysis

HED – Hidden Explosives Detector

IED – Improvised Explosives Device

NAA – Neutron Activation Analysis

NNA – Nanosecond Neutron Analysis

NVS – Improvised Explosive Device (=IED)

PELAN – Portable Elementary Analysis with Neutrons

Pl SE M – Plastic Sheet Explosive Military

PFNA – Pulsed Fast Neutron Analysis

PFTNA – Pulsed Fast-Thermal Neutron Analysis

PGNA – Prompt Gamma Neutron Activation analysis

SNB – National Security Corps

SPEDS – Small Parcel Explosive Detection System

TNA – Thermal Neutron Analysis

TOF – Time-of-Flight

VEDS – Vehicle Explosive Detection System

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R E S U M É

Myšlenky neutronových metod detekce výbušnin se rozvíjely ve světě již koncem minulého století. Pomalejší detekce a aspekty ochrany zdraví způsobily, že se tyto přístroje nerozšířily. Avšak metody neutrony do – gama ven jsou nenahraditelné metody objemové detekce výbušnin a jiných ilegálních organických materiálů ve speciálních případech. Jsou proto vhodné pro vyšší stupně bezpečnostních prohlídek zavazadel, nákladních kontejnerů a nástražných výbušných systémů.

Klíčová slova: detekce výbušnin, neutrony do – gama ven, Zpětný rozptyl neutronů, Promptní neutronová aktivační analýza, Pulsní analýza rychlými neutrony, Zobrazování přidružených částic.

S U M M A R Y

The idea of neutron methods for explosives detection was already being developed around the world at the end of the last century. Slower detection and health protection aspects resulted in the use of these devices not being widespread. However, "neutrons in, gamma out" methods are irreplaceable methods for bulk detection of explosives and other illegal organic materials in special cases. They are therefore suitable for higher levels of baggage security checks, cargo containers and improvised explosives devices.

Keywords: explosives detection, neutron-in, gamma-out, neutron backscattering, prompt gamma neutron activation, pulsed fast neutron analysis, associated particle imaging.