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SENSITIVITY OF EXPLOSIVE MATERIALS TO THE ACTION OF ELECTROMAGNETIC FIELDS

The analysis was done to define the most common methods of detection and disposal of explosive objects. According to the principle of their operation, the methods were subdivided into 4 classes. It was established that physical methods are the most effective, and most of them are based on the use of electromagnetic waves with various parameters. To define the degree of effect of electromagnetic waves on explosive materials it was reasonable to study their electromagnetic properties. It is shown that the main parameter that quantitatively characterizes the degree of sensitivity of explosive materials to the action of electromagnetic fields is the dipole moment of their molecules. The molecular structure of the most common explosive materials, in particular hexogen, pentaerythritol tetranitrate and trinitrotoluene, tetryl, lead trinitroresorcinate, mercuryfulminate and lead azide has been analyzed. It is shown that the molecules of these substances have a two-dimensional structure, while the molecules of hexogen, pentaerythritol tetranitrate, and mercury fulminate are symmetrical. It corresponds to the absence of a dipole moment in such molecules. The dipole moments of asymmetric molecules of trinitrotoluene, tetryl, lead trinitroresorcinate, and lead azide were calculated using the method of adding force vectors of dipole moments of interatomic bonds. The calculated data showed that the dipole moments of these substances are significant, so the electromagnetic influence on the activation of these explosive materials cannot be neglected. Partially, the high values of the dipole moments of trinitrotoluene ($\mu(C_7H_5N_3O_6)$=2,55 D) and tetryl ($\mu(C_7H_5N_5O_8)$=9,27 D) can be explained by an increased number of asymmetric bonds with nitrogen that has a high electronegativity. The obtained data can be used for the development of the safety algorithms to provide a safe work of the rescuers during demining of the territory and when using the devices of an active electromagnetic action in order to prevent the uncontrolled detonation of explosive objects.

Keywords: explosion, demining of territories, explosive materials, electromagnetic waves, molecular structure, dipole moment, safety of rescuers

1. Introduction

The latest achievements of science and technology in the defense-&-industrial sector result in an increased variety and lethality of weapons. Mine weapons have an acient history. For the first time, people began to use the powder energy of the explosion a few centuries ago. Now, it is used for killing and maiming manpower, causing damage to available equipment and as a matter of fact destroying it by impact of explosion and shrapnel. In reality, during military conflicts, mine weapons cause losses not only for military units, but also for civilian population, and mainly children.

No military conflict took place without the use of mine weapons. Large areas are contaminated with explosive objects (EOs) that are laid haphazardly keeping no appropriate records in relevant documentation. The main purpose of using mine weapons is the maiming and killing of personnel and destroying equipment by the interaction of the energy of explosion and the fragments. Unfortunately, a large number of incidents have been recorded among the civilian population, the vast majority of which are children.

Today, due to the hostilities in Ukraine, the area of the territory contaminated with EOs makes up 185,000 square kilometers. The most widespread are anti-personnel high-explosive mines, trap mines, anti-tank mines of high-explosive action, anti-personnel mines of fragmentation action, and anti-tank mines of remote mining.

The mine warfare shows the two vectors of development. The first vector is the

adaptation to the canons of the modern maneuver warfare. The methods of manual mining have become more advanced; remote mining tools have been added, enhancing thus the dynamics of combat operations. The second vector that makes mine warfare more effective is the catastrophic lag in mine detection and demining tools. The EOs are used not only for the minefields, but also outside them. In addition, the use of a primitive probe, however with faultless search accuracy, becomes impossible due to the upgraded mines that are triggered before the sapper detects them [1].

Taking into account the canons of modern maneuver warfare, mine weapons obtained the latest methods of perfect manual and remote mining, enhancing thus the warfare dynamics. However, the means of detection and neutralization are at the stage of catastrophic backlog.

The personnel of the subunits of the State Emergency Service, using available metal detectors, has to stay directly in the affected area because there are no means of remote detection of explosive objects, and it results in injuries and losses.

Hence, the existing problem is that the pyrotechnic subunits searching for and deactivating explosive objects with various special design features are facing high danger.

2. Analysis of literary data and problem statement

The demining process of the territories occurs using the means developed in Soviet times. Their principle of operation is based on the induction and radio wave methods of searching for explosive objects. To determine the location of individual anti-tank, anti-personnel, anti-vehicle, and object mines, as well as unexploded air bombs, artillery shells, mortar mines, etc., the pyrotechnic subunits are equipped with the following devices:

- induction and radio mine detectors IMP, IMP-2 (PR-507), MIV, RVM-2M, RVM-2M, RVM-2 (PR-504A), MMP (PR-505);
- bomb detectors (ferromagnetic body detectors) IMB, MBI, OGF;
- tools to search for INM radio blasters (PR-506);
- mechanical equipment: probes, cats, rolling trawls [1].

The personnel of the subunits of the State Emergency Service, using these metal detectors, has to stay directly in the zone of their possible damage, since there are no means of remote detection of explosive objects, and it results in injuries and losses.

Anti-personnel landmines are one of the main reasons for civilian casualties in conflict-affected areas and these present a significant obstacle to the post-war reconstruction [2].

In spite of technological advances attained in the twenty-first century by Western militaries in demining and removing self-made explosive devices, the humanitarian demining largely relies on mid-twentieth century technologies [3]. No single technology can detect all types of landmines under all environmental conditions, and as a matter of fact there is a need to develop multi-sensor detection systems to overcome the limitations of each sensor.

Theintegration of the sensors for the detection of anti-personnel mines is relating to the combination of the ground-penetrating radar and metal detector technologies [4]. An example of the integration of these sensors is the ALIS system [5]. ALIS is a handheld, portable "dual sensor" capable of receiving electromagnetic radiations and a GPR signal along with the location information while being scanned on the ground by a manual operator. But its use becomes impossible due to the improvement of mines that are triggered before the sapper discovers them [1]. Also, reliable and cost-effective de-

tection and geophysical mapping of areas contaminated by unexploded ordnance, such as cluster munitions, abandoned munitions, and improvised explosive devices, depend on the ability to distinguish hazardous objects from metallic ones [6]. The approach of portable manual detection [7] of mines by the movement of the sensor is slow and dangerous for individual operators; therefore, the development of the means for the remote detection and demining becomes an acute question [8].

Promising developments deal with the creation of the safe means controlled by an operator at a safe distance and also with the generation of special maps with terrain markings providing information on the possible presence of explosive objects in certain areas of the terrain and, in general, the maps of sensor signals [9]. These tools can be both a single platform (a hexapod robot and a scanning manipulator) [10] and a system combining a monitoring platform and an unmanned aerial vehicle to identify probable locations of mines that can be confirmed later by a land-based vehicle [11]. The use of such means in combination with multi-sensor systems that have a high probability of detection, low technical risk, and the possibility of combining the collected data will result in decreased losses of pyrotechnic subunits and high rates of the detection of explosive objects. Laser desorption [12], X-ray and γ-radiation sensors, optical radiation sensors, electrochemical and chemical sensors, optical-&-electronic sensors [13], and neutron methods [14] are promising avenues for the remote detection of the explosives. But the effectiveness of all these methods depends to a great extent on the physical-&-chemical and electromagnetic properties of the materials that are searched for.

Hence, the unresolved part of the problem is the uncertainty of the influence of electromagnetic fields with different parameters on the behavior of explosive materials.

3. The purpose and tasks of the research

The purpose of the research was to identify the sensitivity of explosive materials to the action of electromagnetic fields.

To achieve the set goal we need to solve the following problems:

1. Establishing the mechanisms of the effect of available methods of the remote detection of explosive objects on explosive materials.

2. Defining the degree of sensitivity of explosive materials to the action of electromagnetic fields and waves.

4. Research materials and methods

The object of the research is explosive materials used for explosive items of Eastern European production. The subject of research is the sensitivity of explosive materials to electromagnetic fields and waves. The working hypothesis is the availability of the sensitivity of EOs to the action of electromagnetic fields in terms of the value of the dipole moment of the most common explosive materials. The PMN-2 and PFM-1 mines were chosen from the variety of anti-personnel high-explosive mines. The MON-90 and POM-3 mines are considered as anti-personnel fragmentation mines. The TM-62PZ and PTM-3 mines were selected from the variety of anti-transport high-explosive mines. These types of mines are equipped with a cumulative explosive charge of TG-40 (hexogen (RDX) /trotyl (TNT) 60/40) weighing 1,800 g. The materials of the charges of these explosives are considered as explosive materials. High-explosive substances are used for the main charge and these are characterized by the ability to crush nearby objects during the explosion. The most commonly used explosive is TNT (trinitrotoluene) or its mixtures. The chemical resistance of TNT is high; long-term heating at tempera-

tures of up to 130 °C does not change its explosive properties, and it does not lose these properties even after a long stay in water.

The detonators represent a separate element of an increased danger. In the middle of the sleeve there is a charge of tetryl, pentryn (TEN) or hexogen. A cup with a hole on top is pressed into the sleeve from the top. Inside the cup, there is a TNRS warhead and lead azide (or mercury fulminate). Lead azide (or mercury fulminate) has a detonation force high enough to detonate tetryl, pentryn (TEN) or hexogen, but is not sensitive enough to open flame or shock, so the TNRS warhead that reacts perfectly to flame or shock is placed above it, however it is weak for the excitation of tetryl, ten (pentryn) or hexogen.

The degree of polarization of molecules was determined based on the presence and location of polar chemical bonds in the structure of molecules of explosive substances.

5. Establishing the mechanisms of the effect of the remote detection methods on explosive materials

The development of mine weapons does not stand still and it encourages the improvement of mine countermeasures. Detection techniques are based on various methods that are shown in the diagram in Fig. 1.
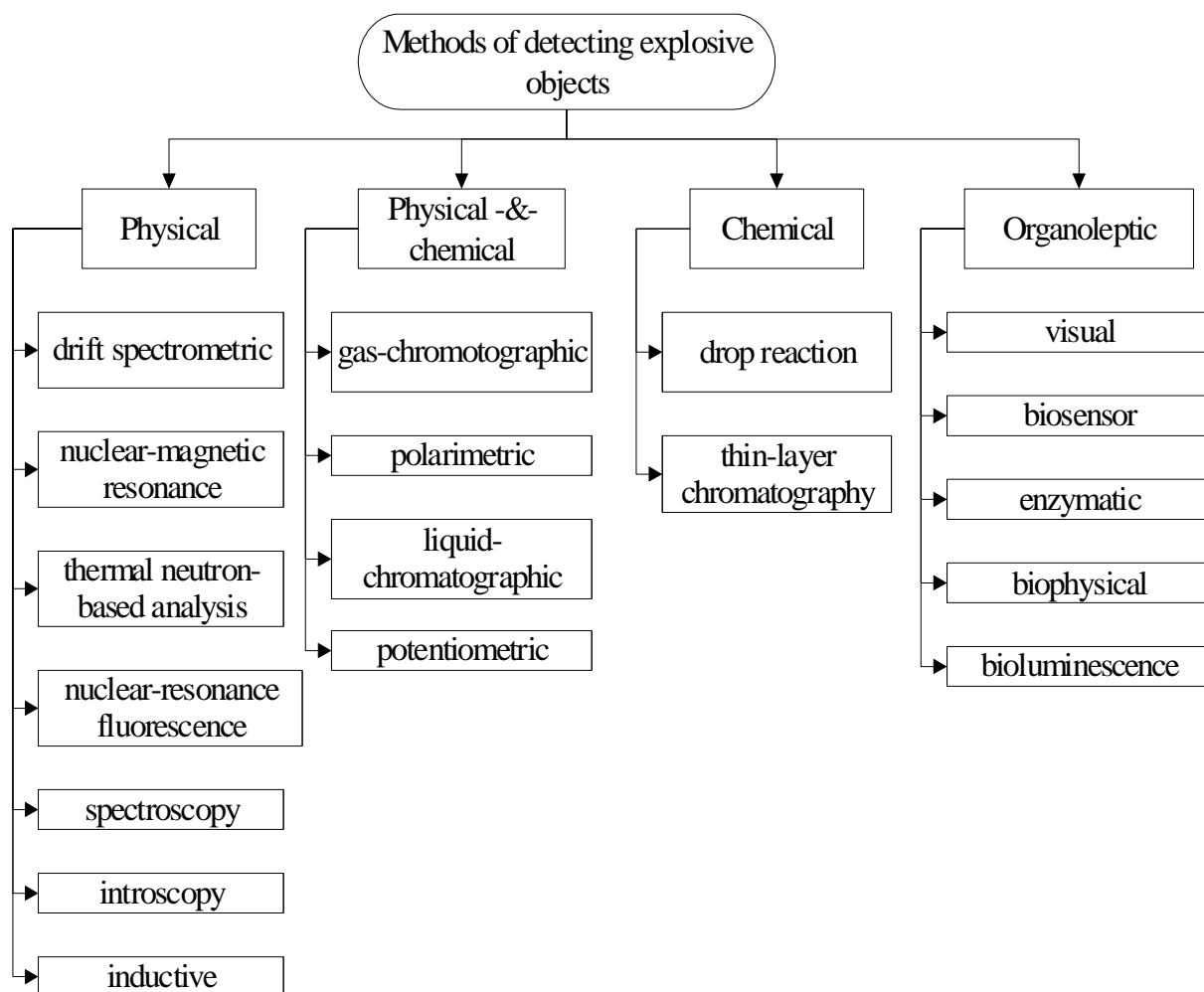

Fig. 1. Method sofdetecting explosive objects

According to the scheme, all the methods of detecting explosive substances and objects can be subdivided into four groups: physical, physical-&-chemical, chemical and organoleptic.

The group of physical methods includes the drift spectrometric method. It consists in that the ionized molecules of explosive substances get into the drift chamber and move to the collector under the action of electric field. Getting to it, these create the current pulse in the electrical circuit that is amplified and processed by the electronic unit. The drift time to the collector depends on the mobility of the ions and the parameters of the electric field, which is the basis for the identification of the analyzed substance [15].

Nuclear methods of detecting the explosives are based on the use of nuclear reactions to find explosive substances hidden, for example, in the luggage or cargo. Nuclear methods of detecting explosives that use neutrons or, in some cases, high-energy (MeV) X-rays for irradiation have been investigated [16]. Examples include thermal neutron analysis, spectroscopy, pulsed fast neutron transmission introscopy, associated particle imaging, and nuclear resonance fluorescence [17].

The inductive method relies on an inductive balance, i.e. several inductance coils are used, one transmitting and one or two receiving, forming an inductive sensor. All the coils are arranged in space in such a manner that the signal from the transmission coil, in the absence of metal objects nearby, is not sent to receiving coils, that is, the entire system is supposed to be balanced and the output signal is expected to be equal to zero.

Physical-&-chemical methods include the gas-chromatographic method that is based on the detection of particles of an explosive substance due to the distribution of its components at the phase boundary of the highly pure carrier gases and a sensitive sorbent. The liquid chromatographic method is based on the detection of the particles of an explosive substance due to its properties to dissolve in carrier liquids and remain on the sorbent for a certain time. The potentiometric method is based on a change in the electrical resistance of a substance under the action of electric current. Polarimetric method presupposes that each substance has its own spectrum under the effect of the stream of light [18].

Chemical methods include the drop reaction method (drop tests), and it is based on a change in the color of traces of an explosive substance under the action of a certain chemical reagent. The method of thin-layer chromatography is based on the properties of the explosive substance to decompose into pure substances under certain conditions (a saturated steam-air mixture of solvents). This group of methods is designed to detect explosive substances on various surfaces, skin, and clothing.

Organoleptic methods include the visual method that is based on the studies of recognizable external signs of explosive substances and devices. The biophysical method, which, in its turn, is subdivided into the following:
– the biosensor method is based on the detection of nitrogen-containing substances with the help of dogs, pigs, etc.;
– the bioluminescence method is based on the detection of the remnants of an explosive substance on hands, clothes, etc., using the UV-luminescence.

The enzymatic method is based on the detection of microparticles of an explosive substance on hands, luggage, etc. when applied to a specially treated tampon.

One of the modern methods of detecting explosive objects is a nuclear method. Nuclear methods designed for the detection of explosive substances make use of nuclear reactions to detect the explosives hidden, for example, in soil. Nuclear methods of detecting explosives that use neutrons or, in some cases, high-energy (MeV) X-rays for irradiation have been studied. Examples of the activation of the neutron system include:
– pulsed fast neutron analysis (PFNA);

– fast neutron analysis (FNA);
– thermal neutron analysis (TNA).

All three systems are based on the interaction of neutrons with the objects undertest and the detection of resulting gamma rays to determine emitted elements. TNA uses thermal neutron capture to generate gamma rays. FNA and PFNA use fast neutron scattering to generate gamma rays. In addition, PFNA uses a pulsed collimated neutron beam. As a result PFNA generates a three-dimensional elemental image of the object under test [16]. The Thermal Neutron Analysis (TNA) detector was developed as a validation sensor for Canada's multi-sensor landmine detector system mounted on the ILDP vehicle [17].

ILDP is the only multi-sensor mine detection system with a confirmation sensor that can reduce false alarms to an acceptable level. It has been experimentally proven that TNA is able to detect anti-tank and large anti-personnel mines in acceptably short periods of time. It performed well in extreme climates, in Canadian and American stand-alone tests, and in US ILDP full-system tests. The TNA system is used to determine the level of nitrogen in soil. Since all explosives contain between 15 % and 40 % nitrogen, the detection of high levels of nitrogen is indicative of the presence of a land mine. Using a 100-μg California-252 neutron source, the TNA system studies the region of interest for the neutron radiation. After capturing thermal neutrons, any available nitrogen emits a certain amount of gamma rays, which are picked up by a ring of four custom-made sodium iodide detectors of 7,62 x 7,62 cm. For landmine detection, a maximum energy transition of these gamma rays occurs at 10,835 MeV [14].

During operation, the TNA system acquires at first the background spectrum. Afterwards, the TNA detection subsystem moves to the target location of interest with or without the mines. Next, another set of spectra is obtained. Afterwards, the probability of the presence of a land mine is calculated by the TNA system based on the number of redundant responses in the area of interest.

6. Determining the degree of sensitivity of explosive materials to electromagnetic fields and waves

One of the main electromagnetic properties of explosive materials is dielectric heating. Heating is caused by the dipole polarization losses of dielectrics.

A distinctive feature of the dielectric heating is the volumicity of the heat released in the heated medium. Themicrowave heating is characterized by a small depth of penetration and the surface heating, as well as inhomogeneity of heating in the space of standing waves. Homogeneity is achieved due to the thermal conductivity of the material. Compared to the induction heating that is used to heat electrically conductive materials by an alternating current with a frequency of no more than 30 MHz, the dielectric heating is usually carried out using higher frequencies.

The microwave heating uses electromagnetic waves with frequencies above 100 MHz. When using electromagnetic microwave waves, heating is caused by the molecular dipole rotation in the dielectric. The forced oscillations of polar molecules under the action of an external electric field result in the intermolecular friction, and as a result, heat is released throughout the entire dielectric. In non-ideal dielectric materials (partially conducting the electric current), additional heating occurs due to conductivity.

That is, the sensitivity of the explosive material to the influence of electromagnetic waves is determined by the dipole moment of the molecules of these materials. The dipole moment of molecules, in its turn, depends on the polarization of chemical bonds

in the structure of these molecules. The polarization of chemical bonds occurs due to the asymmetry (displacement) of the electron density that binds the molecular orbital of the covalent bond. If the atoms forming a covalent bond are the same and carry the same or similar electronegativity substituents, and the distribution of the electron plane is symmetrical with respect to the plane, the perpendicular bond and the crossing bond at equal distances from the atoms then such bonds are called non-polar.

A polar bond has a constant electric dipole moment due to the divergence of the centers of gravity of the negatively charged electrons and the positively charged nuclei. Most covalent bonds are polar. Molecules with a polar bond are usually much more reactive than nonpolar molecules. Polarization of bonds makes a significant contribution to the electric dipole moment of a molecule.

The dipole moment of a polarized bond can result in the polarization of neighboring bonds in the molecule (inductive or I-effect), but this effect is quickly weakened by a chain of σ-bonds. In the case of the presence of a system of connected π-bonds in the molecule, a strong influence of the mesomeric or M-effect of the electron delocalization on the polarization of the bond is possible—up to the polarization.

In order to determine the dipole moment of the molecules of explosive materials, let's consider the structure of their molecules (Fig. 2).
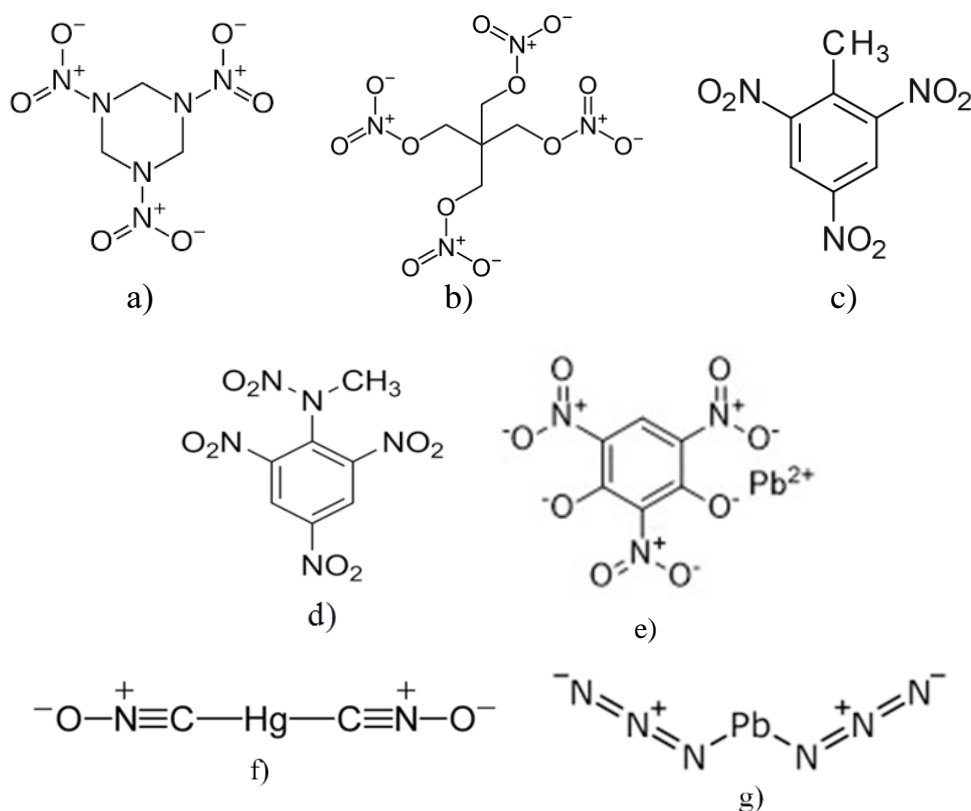

Fig. 2. Molecular structures: a – hexogen; b – pentaerythritol tetranitrate; c – trinitrotoluene; d – tetryl; e – lead trinitroresorcinate; f – mercury fulminate; g – lead azide

The bond polarity is conditioned by the displacement of the bonding electron pair to one of the atoms that results in the formation of a dipolemeasured by the dipole moment (m) the product of the final charge (q) by the distance between the charges (l): m=q*l. Therefore, the dipole moment is increased with the accumulation of the charges during their distribution and an increase in the distance between positive and negative charges.

The dipole moment of a molecule containing more than two atoms depends both

on the polarity of the bonds and the molecular geometry. A polyatomic molecule can have a dipole moment only if its bonds are polar. However, even in the presence of polar bonds, the molecule as a whole can have a dipole moment, if the bonds are directed, so their polarities are mutually compensated. Let's consider the dipole moments of some chemical bonds (Tab. 1) and the electronegativity of individual atoms (Tab. 2).

Tab. 1. Dipole moments (μ) of frequently occurring bonds

Chemical bond	Dipole moment	Chemical bond	Dipole moment
H — F	1,9	H — O	1,5
H — Cl	1,1	C — F	1,4
H — Br	0,8	C — O	0,7
H — I	0,4	C — N	0,2
H — C	0,3	C — O	2,4
H — N	1,3	C = N	3,6

Tab. 2. A series of the electronegativity of some elements

Element	Electronegativity	Element	Electronegativity
Na	0,9	S	2,5
Li	1,0	I	2,5
Mg	1,2	Br	2,8
Si	1,8	Cl	3,0
P	2,1	N	3,0
H	2,1	O	3,5
C	2,5	F	4,0

The boiling point of organic liquids is increased with an increase in the molecular dipole moment. The gravity energy (E) between dipole molecules obeys the dependence:

$$E = m^4/d^6,\tag{1}$$

where m is the dipole moment; d is the distance between the centers of thedipoles.

Calculations of the dipole moments of molecules containing several polar groups can, of course, be done by adding up all the group moments in pairs, and then doing the same with resulting vectors. A much more convenient method of calculation is through projections of the dipole moment vector onto arbitrarily chosen coordinate axes:

$$\mu = (m_x^2 + m_y^2 + m_z^2)^{1/2}.\tag{2}$$

The projection of the dipole moment vector onto the corresponding axis consists of the sum of the projections of all group moments onto this axis. Thus, for a molecule including n polar groups:

$$\mu = \left[\left(\sum_{i=1}^{n} m_{xi} \right)^2 + \left(\sum_{i=1}^{n} m_{yi} \right)^2 + \left(\sum_{i=1}^{n} m_{zi} \right)^2 \right]^{1/2}.\tag{3}$$

To do calculations according to the formula, it is necessary to know the angles of the inclination of the vectors of group moments to coordinate axes. In some cases, especially for planar molecules, these angles can be easily calculated by knowing the valence angles. In many cases, when calculating the dipole moments of molecules, it is more convenient to use not the bond moments but the moments of individual atomic

groups. For example, when analyzing the dipole moments of aromatic nitrocompounds, it is not necessary to consider separately the moments of C–N, N=O, N→O bonds, but it is advisable to introduce the resulting value of the μ_{NO2} group moment. The value of the group moment in the aromatic series is taken as the value of the dipole moment of monosubstituted benzene, and in the aliphatic series it is the value of the corresponding monosubstituted methane.

If the molecule contains two polar groups with moments μ_1 and μ_2, rotates freely around the axes a_1 and a_2, respectively, and the angles formed by the directions of the axes of rotation and the vectors of group moments are θ_1 and θ_2, and the axes themselves form an angle ω_{12} between themselves, then the total moment is calculated by the formula.

$$\mu=(\mu_1^2+\mu_2^2+2\mu_1\mu_2\cos\theta_1\cos\theta_2\cos\omega_{12})^{\frac{1}{2}}. \qquad (4)$$
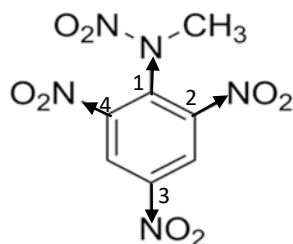
Let's calculate the dipole moments of explosive materials.

Trinitrotoluene
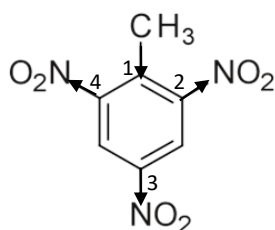
$CH_3(1)$	$m_x=0$	$m_y=-0,37$
$NO_2(2)$	$m_x=4,01\cos60°$	$m_y=4,01\sin60°$
$NO_2(3)$	$m_x=0$	$m_y=-4,01$
$NO_2(4)$	$m_x=-4,01\cos60°$	$m_y=4,01\sin60°$
$\sum m_{xi}=0$		$\sum m_{yi}=2,55$

$$\mu(C_7H_5N_3O_6)=\sqrt{0^2+(2,55)^2}=2,55D$$

Tetryl

$N+NO_2+CH_3(1)$	$m_x=0$	$m_y=2,7+4,01-0,34$
$NO_2(2)$	$m_x=4,01\cos60°$	$m_y=4,01\sin60°$
$NO_2(3)$	$m_x=0$	$m_y=-4,01$
$NO_2(4)$	$m_x=-4,01\cos60°$	$m_y=4,01\sin60°$
$\sum m_{xi}=0$		$\sum m_{yi}=6,34$

$$\mu(C_7H_5N_5O_8)=\sqrt{0^2+(6,34)^2}=6,34D$$

Lead azide
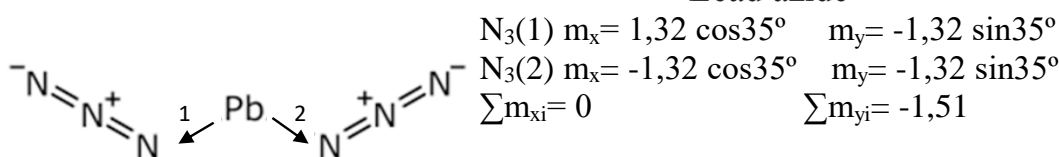
$N_3(1)$	$m_x=1,32\cos35°$	$m_y=-1,32\sin35°$
$N_3(2)$	$m_x=-1,32\cos35°$	$m_y=-1,32\sin35°$
$\sum m_{xi}=0$		$\sum m_{yi}=-1,51$

$$\mu(Pb(N_3)_2)=\sqrt{0^2+(-1,51)^2}=1,51D$$

Lead trinitroresorcinate
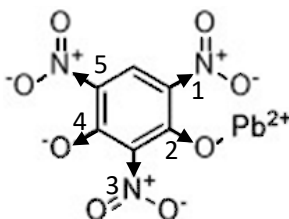
$NO_2+Pb(1)$	$m_x=(4,01+0,54)\cos60°$	$m_y=(4,01+0,54)\sin60°$
$O+Pb(2)$	$m_x=(2,1+1,1)\cos60°$	$m_y=-(2,1+1,1)\sin60°$
$NO_2(3)$	$m_x=0$	$m_y=-4,01$
$O(4)$	$m_x=-2,1\cos60°$	$m_y=-2,1\sin60°$
$NO_2(5)$	$m_x=-4,01\cos60°$	$m_y=4,01\sin60°$
$\sum m_{xi}=0.82$		$\sum m_{yi}=-1,19$

$$\mu(C_6H(NO_2)_3(OPb)_2)=\sqrt{0,82^2+(-1,19)^2}=1,45D$$

Fig. 2 shows that the molecules of hexogen, pentaerythritol tetranitrate and mercury fulminate are symmetric, respectively, their dipole moment will be equal to 0 (μ ($C_3H_6N_6O_6$)=0; μ ($C_5H_8(ONO_2)_4$)=0; μ ($Hg(ONC)_2$)=0). Therefore, the calculations of the dipole moment for trinitrotoluene, tetryl, and lead azide are given below.

7. Discussing the results of determining the sensitivity of explosive materials to the action of electromagnetic fields

The specified classes of the methods used for the remote detection and disposal of explosive objects have shown that all of them have a direct or indirect effect on the material of these objects. At the same time, these can be subdivided into methods that are focused on the effect on the EO body materials and the methods that affect the explosive material itself. However, due to the fact that each EO represents a solid structure made of the body materials and explosive materials, the impact on the explosive material cannot be neglected for any option. In some cases, there are EOs that have no casing based on solid explosive materials.

The analysis showed that it is the electromagnetic method of the remote detection of EOs that has become the most popular today. Therefore, there is a need for studying the effect of electromagnetic waves on explosive materials. During the analysis of the mechanism of the effect of electromagnetic waves on the explosive material, it was established that the dielectric heating by waves with a frequency above 100 MHz can result in its explosion. A specific feature of the obtained results is the determination of the degree of sensitivity of explosive materials in terms of the value of the dipole moment of their molecules. Calculation of the dipole moments of the molecules of the main explosive materials showed that such substances as hexogen, pentaerythritol tetranitrate and mercury fulminate have no dipole moment.

Accordingly, μ ($C_3H_6N_6O_6$)=0, μ ($C_5H_8(ONO_2)_4$)=0 та μ ($Hg(ONC)_2$)=0. It is explained by the symmetrical structure of their molecules, where the actions of polar bonds are compensated by the same bonds in the opposite direction. That is, such substances are insensitive to electromagnetic fields and waves. Since the structure of the molecules of all explosive substances considered in this scientific paper is two-dimensional, the use of the method of adding the force vectors of dipole bonds allows us to simplify the calculations with a satisfactory error (<10 %). Calculations showed that such different molecular structures as lead trinitroresorcinate ($C_6H(NO_2)_3(OPb)_2$) and lead azide ($Pb(N_3)_2$) have close dipole moment values of 1,55 D and 1,45 D, respectively. At the same time, it should be noted that such a result cannot be explained by the content of Pb, because the types of interatomic bonds with lead and their number differ significantly. At the same time, such substances as trinitrotoluene ($C_7H_5N_3O_6$) and tetryl ($C_7H_5N_5O_8$) have a molecular structure similar to that of hexogen ($C_3H_6N_6O_6$), but at the same time they differ significantly in terms of the dipole moment. The dipole moment for trinitrotoluene is quite high, and it is 2,55 D that is higher than the average value for organic substances. However, the dipole moment of tetryl is generally abnormally high, i.e. 9,27 D. In part, such a high value of the dipole moment for tetryl can be explained by the significant content of nitrogen that has a significant electronegativity of 3 (Tab. 2). However, for the final determination of such an abnormally high value of the dipole moment of tetryl, it is necessary to conduct additional studies, and it is not the task of this research.

8. Conclusions

1. The main methods of remote detection and disposal of explosive objects have been analyzed and classified. It was established that all methods can be subdivided

into 4 classes according to the principle of action: physical, physical-&-chemical, chemical and organoleptic. Each method differs by the detection reliability, the time of analysis, autonomy and material consumption. Based on the comparison of these characteristics, the most optimal methods for the use by operational and rescue subunits when clearing a large area of the territory to remove explosive devices of unknown design are the electromagnetic method and the method of neutron analysis. Since the method of neutron analysis is only developing, the main attention in further research should be paid to the mechanisms of interaction of the electromagnetic field with explosive objects.

2. Using the method of adding force vectors, dipole moments were calculated for the main explosive materials, namely trinitrotoluene(μ ($C_7H_5N_3O_6$)=2,55 D), tetryl (μ ($C_7H_5N_5O_8$)=9,27 D), lead azide (μ ($Pb(N_3)_2$)=1,45D) and lead trinitroresorcinate (μ ($C_6H(NO_2)_3(OPb)_2$)=1,51D). These materials were selected for research based on the analysis of the structural composition of the most common explosive objects. Estimating the dipole moment of molecules of explosive materials enables the assessment of the sensitivity of explosive materials to electromagnetic fields and waves. According to the calculation, the greatest danger present the explosive objects containing tetryl, when exposed to electromagnetic waves. It was established that electromagnetic waves have no activating effect on such explosive materials as hexogen, pentaerythritol tetranitrate and mercury fulminate, as these have μ=0D, and it is explained by the two-dimensional symmetrical structure of their molecules.

References

1. Barbashyn, V. V., Nazarov, O. O., Ryutin, V. V. (2010). «Osnovy orhanizatsii pirotekhnichnykh robit. Natsionalnyi universytet tsyvilnohozakhystu Ukrainy». Basics of organizing pyrotechnic works. National University of Civil Defence of Ukraine, 353. Available at: http://eprints.kname.edu.ua/46622/1/%D0%9D%D0%9F%D0%9E%D0%9E%D0%9F%D0%A0.pdf

2. Prem, M., Purroy, M. E., Vargas, J. F. (2022). Landmines: The local effects of demining. Available at: http://tse-fr.eu/pub/126623

3. Dorn, A. W. (2019). Eliminating Hidden Killers: How Can Technology Help Humanitarian Demining? Stability: International Journal of Security and Development, 8(1), 5. doi: 10.5334/sta.743

4. Cardona, L., Jiménez, J., Vanegas, N. (2014). Landmine detection technologies to face the demining problem in Antioquia. Dyna, 81(183), 115–125. doi: 10.15446/dyna.v81n183.37441

5. Sato, M., Kikuta, K., Chemyak, I. (2018). Dual Sensor "ALlS" for Humanitarian Demining. In 2018 17th International Conference on Ground Penetrating Radar (GPR), 1–4. doi: 10.1109/ICGPR.2018.8441662

6. Schultz, G. M., Keranen, J., Miller, J. S., Shubitidze, F. (2014). Acquisition and processing of advanced sensor data for ERW and UXO detection and classification. In Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIX, 9072, 112–120. doi: 10.1117/12.2050876

7. Yinon, J. (2002). Field detection and monitoring of explosives. TrAC Trends in Analytical Chemistry, 21(4), 292–301. doi: 10.1016/S0165-9936(02)00408-9

8. Habib, M. K. (2007). Humanitarian demining: reality and the challenge of technology–the state of the arts. International Journal of Advanced Robotic Systems, 4(2), 19. doi: 10.5772/5699

9. Pakhnyts, I., Khrustalova, S., Khrustalev, K. (2022). System for detection and identification of potentially explosive objects in open area. Innovative Technologies and Scientific Solutions for Industries, 2(20), 106–112. doi: 10.30837/ITSSI.2022.20.106

10. Montes, H., Mena, L., Fernández, R., Sarria, J., Armada, M. (2016). Inspection platform for applications in humanitarian demining. In Assistive Robotics: Proceedings of the 18th International Conference on CLAWAR 2015, 446–453. doi: 10.1142/9789814725248_0055

11. De Cubber, G., Balta, H., Lietart, C. (2014). Teodor: A semi-autonomous search and rescue and demining robot. In Applied Mechanics and Materials, 658, 599–605. doi: 10.4028/www.scientific.net/AMM.658.599

12. Akmalov, A. E., Chistyakov, A. A., Dubkova, O. I., Kotkovskii, G. E., Spitsyn, E. M., Buzinov, N. M. (2016, October). Laser desorption of explosives traces at ambient conditions. In Optics and Photonics for Counterterrorism, Crime Fighting, and Defence XII, 9995, 110–116. doi: 10.1117/12.2241813

13. Bielecki, Z., Janucki, J., Kawalec, A., Mikołajczyk, J., Pałka, N., Pasternak, M., Stacewicz, T. (2012). Sensors and systems for the detection of explosive devices-an overview. Metrology and Measurement Systems, 19(1), 3–28. doi: 10.2478/v10178-012-0001-3

14. Cousins, T., Jones, T., Brisson, J., McFee, J., Jamieson, T., Waller, E., Selkirk, E. (1998). The development of a thermal neutron activation (TNA) system as a confirmatory non-metallic land mine detector. Journal of Radioanalytical and Nuclear Chemistry, 235(1–2), 53–58. doi: 10.1007/bf02385937

15. Buryakov, I. (2011). Detection of explosives by ion mobility spectrometry. Journal of Analytical Chemistry, 66(8). doi: 10.1134/S1061934811080077

16. Kagan, A. (2022). Counterterrorist detection techniques of explosives by vapor sensors (handheld). In Counterterrorist Detection Techniques of Explosives, 235–251. doi: 10.1016/B978-0-444-64104-5.00012-6

17. Clifford, E. T., Ing, H., McFee, J. E., Cousins, T. (1999, October). High rate counting electronics for a thermal neutron analysis land mine detector. In Penetrating Radiation Systems and Applications, 3769, 155–166. doi: 10.1117/12.363677

18. Ishchenko, A. V., Kobets, M. V. (2005). «Zasoby i metody vyiavlennia vybukhovykh rechovyn ta prystroiv u borotbi z teroryzmom. Natsionalna akademiiavnutrishnikhspravUkrainy». Means and methods of detecting explosive substances and devices in the fight against terrorism. National Academy of Internal Affairs of Ukraine, 148. Available at: http://elar.naiau.kiev.ua/bitstream/123456789/18996/1/Kobets%20M.V.%20Zasoby%20i%20metody%20vyaiyvlenaiy%20VP.pdf

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ЧУТЛИВІСТЬ ВИБУХОНЕБЕЗПЕЧНИХ МАТЕРІАЛІВ ДО ДІЇ ЕЛЕКТРОМАГНІТНОГО ПОЛЯ

Проаналізовано найбільш поширені методи виявлення та знешкодження вибухонебезпечних предметів. За принципом їх дії методи розбито на 4 класи. Встановлено, що найбільшу ефективність мають фізичні методи, більшість з яких засновано на використанні електромагнітних хвиль з різними параметрами. Для визначення ступеню впливу електромагнітних хвиль на вибухонебезпечні матеріали досліджено їх електромагнітні властивості. Показано, що основним па-

раметром, який кількісно характеризує ступінь чутливості вибухонебезпечних матеріали до дії електромагнітного поля є дипольний момент їх молекул. Проаналізовано структуру молекул найбільш поширених вибухонебезпечних матеріалів – гексогену, пентаеритріттетранітрату та тринітротолуолу, тетрилу, тринітрорезорцинату свинцю, фульмінату ртуті та азиду свинцю. Показано, що молекули цих речовин мають двовимірну структуру, а молекули гексогену, пентаеритріттетранітрату та фульмінату ртуті є симетричними. Це відповідає відсутності дипольного моменту у таких молекулах. Дипольні моменти несиметричних молекул тринітротолуолу, тетрилу, тринітрорезорцинату свинцю та азиду свинцю розраховані методом додавання векторів сил дипольних моментів міжатомних зв'язків. Результати розрахунків показали, що дипольні моменти цих речовин є значними, тому електромагнітним впливом на активацію цих вибухонебезпечних матеріалів нехтувати неможна. Частково високі показники дипольних моментів тринітротолуолу (μ ($C_7H_5N_3O_6$)=2,55 D) та тетрилу (μ ($C_7H_5N_5O_8$)=9,27 D) пояснюється підвищенню кількістю несиметричних зв'язків з нітрогеном, який має високу електронегативність. Отримані результати можна використовувати при розробці безпекових алгоритмів роботи рятувальників при розмінуванні території та при використання приладів із активною електромагнітною дією з метою попередження неконтрольованого підриву вибухонебезпечних предметів.

Ключові слова: підрив, розмінування територій, вибухонебезпечні матеріали, електромагнітні хвилі, структура молекули, дипольний момент, безпека рятувальників

Література

1. Барбашин В. В., Назаров О. О., Рютін В. В. Основи організації піротехнічних робіт. Національний університет цивільного захисту України, 2010. 353 с. URL: http://eprints.kname.edu.ua/46622/1/%D0%9D%D0%9F%D0%9E%D0%9E%D0%9F%D0%A0.pdf

2. Prem M., Purroy M. E., Vargas J. F. Landmines: The local effects of demining. 2022. URL: http://tse-fr.eu/pub/126623

3. Dorn A. W. Eliminating Hidden Killers: How Can Technology Help Humanitarian Demining. Stability: International Journal of Security and Development. 2019.Vol. 8(1). P. 5. doi: 10.5334/sta.743

4. Cardona L., Jiménez J., Vanegas N. Landmine detection technologies to face the demining problem in Antioquia. Dyna. 2014. Vol. 81(183). P. 115–125. doi: 10.15446/dyna.v81n183.37441

5. Sato M., Kikuta K., Chemyak I. Dual Sensor «ALIS» for Humanitarian Demining. In 2018 17th International Conference on Ground Penetrating Radar (GPR). 2018. P. 1–4. doi: 10.1109/ICGPR.2018.8441662

6. Schultz G. M., Keranen J., Miller J. S., Shubitidze F.Acquisition and processing of advanced sensor data for ERW and UXO detection and classification. In Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XIX. 2014. Vol. 9072. P. 112–120. doi: 10.1117/12.2050876

7. Yinon J. Field detection and monitoring of explosives. TrAC Trends in Analytical Chemistry. 2002. Vol. 21(4). P. 292–301. doi: 10.1016/S0165-9936(02)00408-9

8. Habib M. K.Humanitarian demining: reality and the challenge of technology–the state of the arts. International Journal of Advanced Robotic Systems. 2007. Vol. 4(2). P. 19. doi: 10.5772/5699

9. Pakhnyts I., Khrustalova S., Khrustalev K. System for detection and identification of potentially explosive objects in open area. Innovative Technologies and Scientific Solutions for Industries. 2022. Vol. 2(20). P. 106–112. doi: 10.30837/ITSSI.2022.20.106

10. Montes H., Mena L., Fernández R., Sarria J., Armada M. Inspection platform for applications in humanitarian demining. In ASSISTIVE ROBOTICS: Proceedings of

the 18th International Conference on CLAWAR 2015. 2016. P. 446–453. doi: 10.1142/9789814725248_0055

11. De Cubber G., Balta H., Lietart, C. Teodor: A semi-autonomous search and rescue and demining robot. In Applied Mechanics and Materials. 2014. Vol. 658. P. 599–605. doi: 10.4028/www.scientific.net/AMM.658.599

12. Akmalov A. E., Chistyakov A. A., Dubkova O. I., Kotkovskii G. E., Spitsyn E. M., Buzinov N. M. Laser desorption of explosives traces at ambient conditions. In Optics and Photonics for Counterterrorism, Crime Fighting, and Defence XII. 2016. Vol. 9995. P. 110–116. doi: 10.1117/12.2241813

13. Bielecki Z., Janucki J., Kawalec A., Mikołajczyk J., Pałka N., Pasternak M., Pustelny T., Stacewicz T. Sensors and systems for the detection of explosive devices-an overview. Metrology and Measurement Systems. 2012. Vol. 19(1). P. 3–28. doi: 10.2478/v10178-012-0001-3

14. Cousins T., Jones T., Brisson J., McFee J., Jamieson T., Waller E., Le May F., Ing H., Clifford E., Selkirk E. The development of a thermal neutron activation (TNA) system as a confirmatory non-metallic land mine detector. Journal of Radioanalytical and Nuclear Chemistry. 1998. Vol. 235(1–2). P. 53–58. doi: 10.1007/bf02385937

15. Buryakov I. Detection of explosives by ion mobility spectrometry. Journal of Analytical Chemistry. 2011. № 66(8). doi: 10.1134/S1061934811080077

16. Kagan A. Counterterrorist detection techniques of explosives by vapor sensors (handheld). In Counterterrorist Detection Techniques of Explosives. 2022. P. 235–251. doi: 10.1016/B978-0-444-64104-5.00012-6

17. Clifford E. T., Ing H., McFee J. E., Cousins, T.High rate counting electronics for a thermal neutron analysis land mine detector. In Penetrating Radiation Systems and Applications. 1999. Vol. 3769. P. 155–166. doi: 10.1117/12.363677

18. Іщенко А. В., Кобець М. В. Засоби і методи виявлення вибухових речовин та пристроїв у боротьбі з тероризмом. Національна академія внутрішніх справ України, 2005. 146 с. URL: http://elar.naiau.kiev.ua/bitstream/123456789/18996/1/Kobets%20M.V.%20Zasoby%20i%20metody%20vyaiyvlenaiy%20VP.pdf