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**“Commercial Systems for the Direct Detection of Explosives  
(for Explosive Ordnance Disposal Tasks)”**

**ExploStudy, Final Report**

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## 1. Introduction:

The main goal of this study, carried out by the author on behalf of the Swiss Defence Procurement Agency (DPA), was to characterise existing technologies, and identify corresponding commercially available systems, for the **direct detection of explosives for Explosive Ordnance Disposal (EOD) tasks**. *Systems should be able to determine if a given piece of munition contains explosives or is inert, and ideally in the former case to establish the type of explosive* (see also Annex A2.1). This will be often referred to in the following as the “*task at hand*”, or the “*task of interest to us*”. Note that **the object in questions has already been detected by other means** (usually visually, e.g. lying on the surface) – **what is needed is the capacity to characterise its contents** (explosive or inert).

Systems should preferably be able to make a detection under the following assumptions:

- The object under analysis should NOT be moved (at least as long as the state of the detonator is unknown). It should preferably also NOT be touched nor swiped.
- The Unexploded Ordnance (UXO) is at least *partially visible*; it could nevertheless still be necessary to detect the explosive in the earth, i.e. buried explosive material.
- *Explosives* of primary interest are those based on TNT, RDX (Hexogen), PETN (Nitropenta), HMX (Octogen), and possibly picric acid for older munition. Explosives of secondary interest are black powder, ammonium nitrate, and phosphorus (in incendiary devices).
- *Minimum interesting explosive mass* is in the 50 gram range.
- The system has to be fairly *mobile*.
- (If possible) Priority should be given to the detection of *Nitrogen* (N), *Oxygen* (O) and *Carbon* (C) (in particular N and O).

It was in fact agreed to keep the target application and audience somewhat larger at the beginning of the study, before focussing on the task at hand. This on one hand in order to profit from input coming from related fields (in particular airport security, counterterrorism, customs applications, demining tasks, and detection of chemical weapons), on the other hand in order not to exclude possible applications of a system designed for EOD tasks to those same fields.

This broader, initial goal did therefore include the study of commercially available systems for the direct detection of explosives, in sealed (e.g. UXO) as well as non-sealed systems (e.g. “suspicious objects”). The main conclusions will then again be focussed on the task at hand. At first sight bulk explosive detection would seem to be most appropriate for hermetically as well as some non-hermetically sealed systems, whereas trace detection would seem to be most appropriate for non-hermetically sealed systems. We will try to see in the following up to which extent this is true.

### DISCLAIMER

This report is based on public material. A number of companies or organisations developing and producing explosive detection systems are cited for illustrative purposes. These references are not all-inclusive and do not represent endorsement of the corresponding systems.

## 1.1. Properties of Explosives:

A few physical and chemical properties of basic explosives are summarised in Table 1 (the information has been mostly assembled from [YIN99], as well as from [NIJ99a] and [NIJ98]):

Name	Molecular Weight	C	H	N	O	Density (g/cm <sup>3</sup> )	Vapour Pressure (rel.   Torr)	Preferred Trace Det.
<b>TNT</b>	227.13	7	5	3	6	1.65	7.7 ppb   5.8·10 <sup>-6</sup> (25 °C)	Particle (Vap.)
<b>RDX</b>	222.26	3	6	6	6	1.83	6.0 ppt   4.6·10 <sup>-9</sup> (25 °C)	Particle
<b>HMX</b>	296.16	4	8	8	8	1.96	3.95 ppt   3·10 <sup>-9</sup> (100 °C!)	Particle
<b>Tetryl</b>	287.15	7	5	5	8	1.73	7.5 ppt   5.7·10 <sup>-9</sup> (25 °C)	Particle
<b>PETN</b>	316.2	5	8	4	12	1.78	18 ppt   1.4·10 <sup>-8</sup> (25 °C)	Particle
<b>NG</b>	227.09	3	5	3	9	1.59	0.41 ppm   3.1·10 <sup>-4</sup> (26 °C)	Vapour
<b>EGDN</b>	152.1	2	4	2	6	1.49	92.6 ppm   0.07 (25 °C)	Vapour
<b>AN</b>	80.05	–	4	2	3	1.59	12 ppb   9.1·10 <sup>-6</sup> (25 °C)	Particle (Vap.)
<b>TATP</b>	222.23	9	18	–	6	1.2		
<b>DNB</b>	168.11	6	4	2	4	1.58	3.8 ppm   2.9·10 <sup>-3</sup> (25 °C)*	
<b>Picric acid</b>	229.12	6	3	3	7	1.76	7.6 ppt   5.8·10 <sup>-9</sup> (25 °C)*	

**Table 1: Properties of some basic explosives (source: mostly [YIN99], also [NIJ99a, NIJ98]; \*: calculated from [ROS91])**

**TNT** (2,4,6-Trinitrotoluene) is one of the most widely used military explosives, and has been in use for about the last 100 years (most of the production during WWI and WWII). **DNB** (1,3-Dinitrobenzene) was produced in large quantities during WWI (in second place after TNT), and to a lesser extent during WWII. **Picric acid** (2,4,6-trinitrophenol) has been the third most produced explosive during WWI, and to a much lesser extent during WWII. **RDX** (Hexogen) is more recent, was the second most produced explosive during WWII and is still in very wide use today, also in plastic explosives<sup>2</sup>. **PETN** (Nitropenta) is also used in plastic explosives. **HMX** (Octogen) is a very powerful and costly military explosive, which has been employed in solid-fuel rocket propellants and in military high performance warheads. As general references see also [YIN99, HAA94].

Military explosives currently used are mostly a combination of TNT, RDX, PETN, HMX, with a number of organic compounds (waxes, plasticizers, stabilisers, oils, etc.). Examples<sup>3</sup> are **Composition B** (RDX, TNT), **Composition C-4 (or PE 4)** (RDX), **Detasheet** (PETN), **Octol** (HMX, TNT), **Semtex-H** (RDX, PETN), etc. [YIN99].

**Nitroglycerin (NG)** and **Ammonium Nitrate (AN, NH<sub>4</sub>NO<sub>3</sub>)** are used as a basis of other families of explosives (dynamites in the case of NG), typically as high explosive for industrial applications and in solid rocket propellants. Note that pure AN does not contain carbon; it has been widely used to fabricate bombs, but is also widely diffused as a fertiliser. **EGDN** (Ethylene glycol dinitrate) is a transparent, colourless liquid explosive, which has been used in mixtures with NG for low-temperature dynamites. Its use has greatly decreased due to the replacement of dynamites with ammonium nitrate-fuel oil (**ANFO**) and slurry explosives [YIN99].

**Black powder** is a low-order explosive consisting of potassium nitrate (KNO<sub>3</sub>) or sodium nitrate (NaNO<sub>3</sub>), charcoal, and sulphur (it does therefore probably not contain hydrogen). It is used in incendiary devices and as low-order high explosive.

<sup>2</sup> *Plastic explosives* are high-explosive materials that have the general consistency of plastic. They are usually based on RDX and/or PETN. Examples include C-4, Detasheet, and Semtex [NIJ99a].

<sup>3</sup> The main high explosive components are reported in brackets.

### 1.1.1. Chemical Composition:

All high explosives contain inside the molecule the oxygen necessary for the explosive reaction, with the most important oxygen carriers being organic nitro compounds, nitrates, chlorates and perchlorates. Nitrogen is also contained in all the explosives listed above. Explosives are therefore composed of **Carbon (C)**, **Hydrogen (H)**, **Nitrogen (N)** and **Oxygen (O)** (with the few exceptions listed above, at least concerning the basic explosives), and many other organic compounds. Elemental ratios for some common basic explosives are reported in Table 2, derived from Table 1.

*Explosives are, as a group, rich in nitrogen and oxygen, poor in carbon and hydrogen, with a particularly characteristic indicator being the oxygen vs. nitrogen atomic density (in mol/cm<sup>3</sup>, see for ex. Fig. 3.4 [YIN99]). It would nevertheless be necessary, for the application we are considering, to compare the composition of explosives with the inert substances of interest, rather than with the materials commonly employed in security studies (e.g. clothing or plastics, see for example [YIN99]).*

Name	C/O	H/N	C/N	O/N	Nitrogen (weight %)
NG	0.33	1.67	1	3	18.5
TNT	1.17	1.67	2.33	2	18.5
RDX	0.5	1	0.5	1	38.0
PETN	0.42	2	1.25	3	17.7
AN	0	2	0	1.5	35.0

Table 2: Elemental ratios for some common basic explosives, derived from Table 1 (last col.: [YIN99], Table 3.4)

### 1.1.2. Vapour Pressure:

We recall that all solids and liquids emit a certain amount of vapour (usually rapidly increasing with temperature), and that the pressure of the gas phase above them is called **vapour pressure**. Its value corresponds actually to the maximum pressure of the gas which exists above the substance's surface, for example in the space above some TNT contained in closed bottle, when equilibrium has been reached (as many molecules evaporate from the substance's surface as are reabsorbed). *The vapour pressure is therefore a very important indicator of how easily a substance tends to evaporate, and therefore of how likely a detection as vapour is going to succeed.* See also [DIO86, ROS91].

The vapour pressures for mixtures containing pure explosives, e.g. C-4 containing RDX, may in fact be lower [NIJ99a, YIN99 §2.3] than the values quoted in Table 1 for *pure materials*, and change from one mixture to the other even if the basic explosive is the same and in the same quantity. Reasons for this include the presence of other substances in the explosive matrix, such as polymeric binders, plasticizers and/or waxes. In addition, *in real world situations equilibrium might not be reached* due to a number of factors affecting the diffusion and transport of explosive material, such as: packaging and encapsulation, stagnant reflective boundary layer effects, temperature fluctuations, uncontrolled air currents or adhesion of vapour to surrounding surfaces [NAV97, §2.1.2.1.2; NAV9x, NIJ98]. As a result, *the actual vapour pressure can be orders of magnitude lower than the values quoted for equilibrium situations* [NIJ98], such as those in Table 1. All this obviously affects detection efficiency. On the other hand high vapour pressure impurities might be present, thus potentially facilitating detection.

Vapour pressures are often expressed as **relative concentrations** in saturated air, rather than in true pressure units, and are usually expressed in units of **ppm** (parts per million: 1:10<sup>6</sup>, corresponding to one molecule per one million air molecules), **ppb** (parts per billion, 1:10<sup>9</sup>), or **ppt** (parts per trillion, 1:10<sup>12</sup>). Such concentrations are proportional to the true vapour pressure (in torr, or Pascal), as in a given volume and at the same temperature  $n_{\text{expl}}/n_{\text{air}} = p_{\text{expl}}/p_{\text{air}}$ . Indeed, for an ideal gas we have the following relationship between the (vapour) pressure  $p$  (in Pascal, with 1 Torr = 133 Pa), the volume  $V$  (m<sup>3</sup>), the quantity of gas  $n$  measured in moles (e.g. 1 mole TNT = 227.13 grams), and the absolute temperature  $T$  in Kelvin (0 °C ~ 273 K):

$$pV = nRT \Rightarrow n/V = p/RT$$

with  $R$  being the universal gas constant ( $8.31 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ ). The TNT relative concentration at  $25 \text{ }^\circ\text{C}$  for example amounts to  $5.8\cdot 10^{-6}$  torr, or 7.7 ppb, corresponding to about  $0.07 \text{ ng/cm}^3$  ( $1 \text{ ng} = 10^{-9} \text{ g}$ ). An order of magnitude figure for TNT of  $0.1 \text{ ng/cm}^3$  is often encountered. Note that this figure is very small compared to the amount of TNT contained in a typical particle in a fingerprint for example, which might contain several micrograms of TNT ( $1 \text{ } \mu\text{g} = 10^{-6} \text{ g} = 1000 \text{ ng}$ ) [NIJ99a].

As we said the vapour pressure increases quite rapidly with temperature; in the case of solid TNT near room temperature for example it approximately doubles every  $5 \text{ }^\circ\text{C}$ . On the other hand this also implies that explosive vapour detection can become difficult in cold environments, see for example [NAV9x]. One way of increasing the chances of a successful vapour detection might therefore be to heat the object (this could however also increase the amount of interfering vapours).

**ppm** range or higher:

EGDN and NG have relatively high vapour pressures (**ppm** range or higher), which implies that they and their compounds (typically dynamites) are correspondingly “easy” to detect in the vapour phase with existing commercial equipment (e.g. of the IMS or ECD type) and also by the human nose. As a downside of the high vapour pressure, their particle detection might also be possible but less effective due to the tendency of small particles to evaporate rapidly.

**ppb** range:

TNT and AN vapour pressures are already in the **ppb** range and therefore correspondingly difficult to detect in the vapour phase, pushing in many cases the required sensitivity to the detection system’s limits. Particle detection based on surface swiping is therefore usually preferred, with AN being somewhat a special case.

**(sub-)ppt** range:

RDX, Tetryl and PETN and their compounds (in particular **plastic** explosives, and also explosives based on potassium and sodium chlorate) have a very low tendency to evaporate (**ppt** range<sup>4</sup>), with HMX being even a couple of orders of magnitude lower (**sub-ppt** range at room temperature). This makes their vapour based detection indeed very difficult, so that a lot of effort has gone into providing detection of particulate material instead.

### 1.1.3. Particle Detection:

Particle (or particulate) contamination consists of *microscopic solid particles*, often with masses on the order of a few micrograms (many particles will be contained in a typical fingerprint) [NIJ99a]. As explosives tend to be rather “sticky” – they adhere well on surfaces<sup>5</sup> – someone handling a macroscopic piece of it will for example quickly contaminate his or her hands, as well as any additional surfaces that are touched by the hands. Reducing the spread of particulate contamination to zero is actually extremely difficult. As an example, [NAP99] reports that tests using C4 explosives as a model material suggest that, even with a 10% collection efficiency, enough material is left from tenth-generation fingerprints (!) to be detected by current trace explosives detection systems.

Particle detection itself can be carried out by wiping a surface with a swipe pad, usually provided by the equipment manufacturer himself, which will be inserted in the instrument’s sampling port and be analysed. More details will be provided later on. *Sample collection and transport to the detector are therefore indeed key issues* [NIJ99b, NAV97]. More details on the factors influencing contact trace detection are provided in [NAV97 §2.1.2.2, NAP99].

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<sup>4</sup> Some doubts exist on the RDX and PETN values (in some cases the vapour pressure of RDX has been quoted as being larger than that of PETN), but their order of magnitude is correct.

<sup>5</sup> Similar arguments hold by the way for the soil in case of buried explosives (§4.2.1).

#### 1.1.4. Tagging:

Substances can be added to explosives at the time of manufacture, usually in small amounts, to facilitate its detection (**Detection taggants**) and/or its identification after explosion (**Identification taggants**). Detection taggants are typically high vapour pressure compounds (which therefore evaporate much more easily than the explosive itself), such as EGDN, ortho-mononitrotoluene (o-MNT), para-mononitrotoluene (p-MNT), and dimethyldinitrobutane (DMNB) [YIN99]. These substances have vapour pressures similar to those of NG and their presence makes vapour detection of explosives, plastic ones in particular, possible. Tagging, although useful, does however not represent the ultimate solution of the detection problem. Additional considerations on the tagging procedure are for example detailed in [YIN99] and [NAV97]. Detection of taggants is also discussed in [NAV9x].

#### 1.2. Properties of some INERT Fillers:

As said initially, the main task at hand is identifying a UXO as inert or filled with explosives. The inert substances used do often share *physical properties similar to those of explosives*, such as the *density* (e.g. to simulate the same ballistic behaviour). The following substances have been quoted as *possible fillers of inert munition* (where possible the chemical composition is indicated) – note that *most of them do not contain nitrogen*:

- *Hard metals* (e.g. tungsten and alloys) as cores of kinetic projectiles;
- *Concrete* (cement + gravel) in practice bombs ( $\text{Ca}_4(\text{OH})_2\text{Si}_6\text{O}_{15} \cdot 3 \text{H}_2\text{O}$ , +  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  in variable quantity);
- *Plaster* (gypsum) in practice shells ( $\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$ , dihydrate);
- *Sand* (mainly  $\text{SiO}_2$ ) and *Earth* (see below);
- *Loam* or other plasticines (e.g. magnesium based);
- *Wax* and wax based mixtures;
- *Synthetic resins* which can be casted (moulded);
- Other density calibration (tare) substances based for example on stearin (high H content) or carnauba wax (high H density), and quartz flour (mainly  $\text{SiO}_2$ ). The addition of hematite ( $\text{Fe}_3\text{O}_4$ ) is also possible;
- *Air*;
- *Water* or *glycerine and sugar* (in inert versions of chemical munition).

Note that *the earth's crust eight main components are*: oxygen (49.5%), silicon (25.8%), aluminium (7.5%), iron (4.7%), calcium 3.4%), sodium (2.6%), potassium (2.4%), magnesium (1.9%) [HUS99]. Local variations are obviously possible. A “standard” soil contains therefore very little nitrogen, with the exception of areas with high fertiliser content or possibly in presence of vegetation/organic material.



### 1.3. Composition of some Chemical Warfare Agents (CWA):

We will briefly mention bulk explosive detection of Chemical Warfare Agents (CWA), which relies on the detection of characteristic elements such as **Arsenic (As)**, **Bromine (Br)**, **Chlorine (Cl)**, **Fluorine (F)**, **Phosphorus (P)**, and **Sulphur (S)**. Table 3 reports therefore the composition of some CWA, without entering into further details.

<b>Name</b>	<b>C</b>	<b>H</b>	<b>N</b>	<b>O</b>	<b>Cl</b>	<b>P</b>	<b>As</b>	<b>S</b>	<b>F</b>
<b>Lewisite I</b>	2	2	–	–	3	–	1	–	–
<b>Lewisite II</b>	4	4	–	–	3	–	1	–	–
<b>Lewisite III</b>	6	6	–	–	3	–	1	–	–
<b>Clark I (DA)</b>	12	10	–	–	1	–	1	–	–
<b>Clark II (DC)</b>	13	10	1	–	–	–	1	–	–
<b>S-Mustard (HD)</b>	4	8	–	–	2	–	–	1	–
<b>N-Mustard (HN)</b>	6	12	1	–	3	–	–	–	–
<b>Tabun (GA)</b>	5	11	2	2	–	1	–	–	–
<b>Sarin (GB)</b>	4	11	–	2	–	1	–	–	1
<b>Soman (GD)</b>	7	16	–	2	–	1	–	–	1
<b>VX</b>	11	26	1	2	–	1	–	1	–

**Table 3: Composition of some Chemical Warfare Agents (data source: I.U.T. “GIOS” brochure)**

Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

The following Figure provides a useful overview, albeit non-exhaustive, of current Bulk and Trace explosive detection technologies of interest, most of which we are going to discuss in the following.

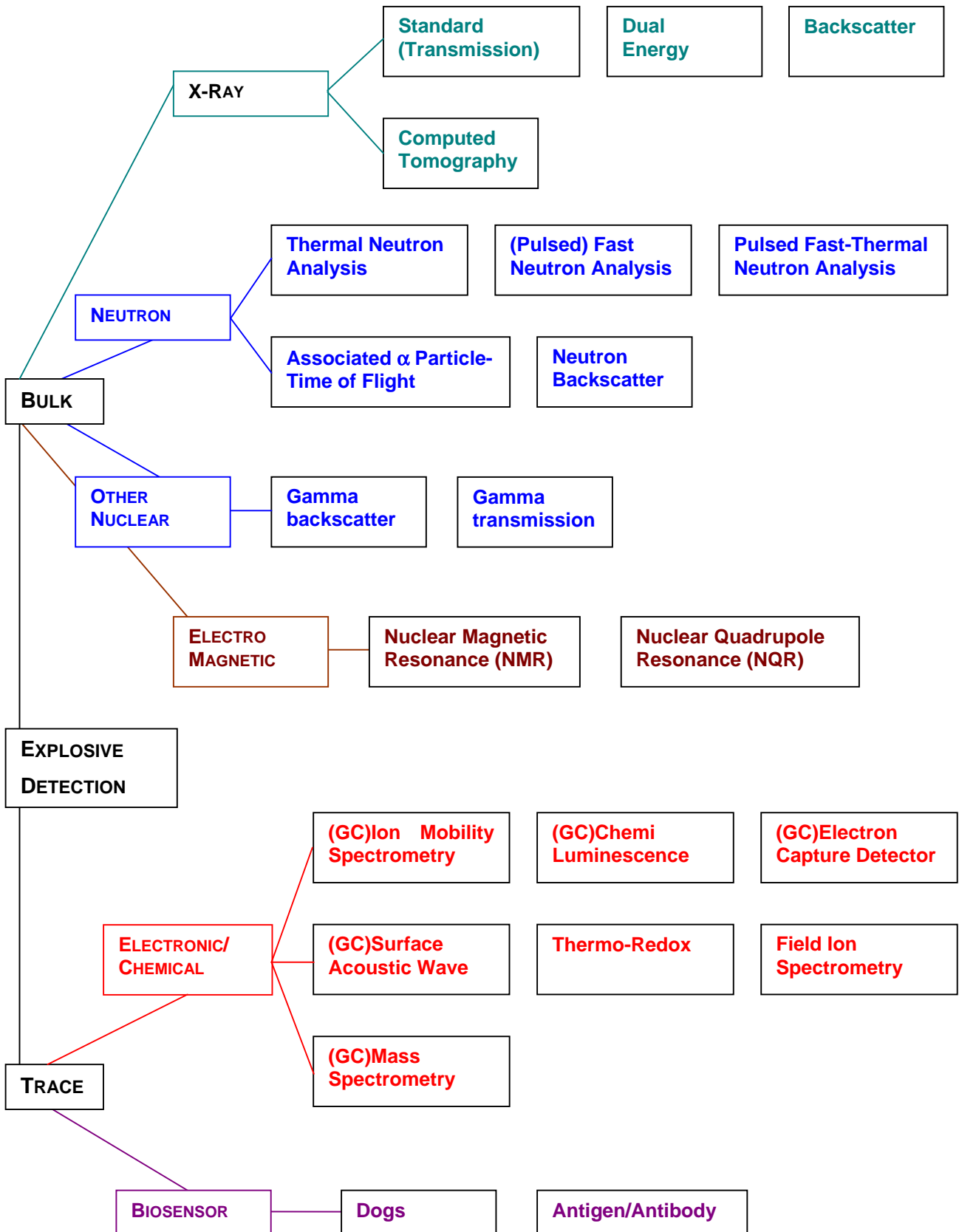


Figure 1: Organization of Current Explosive Detection Technologies (adapted from [NAV97, Fig. 2.1-1])

## 2. BULK Explosive Detection Technologies:

*Direct detection of a macroscopic mass of explosive material*, or bulk explosive detection, can be carried out using some type of *probing radiation*, which has to penetrate the explosive's container(s) and possibly the earth as well in case of buried objects. This restricts the choice to the use of electromagnetic radiation, usually either radiowaves or microwaves (plus static magnetic fields if necessary), X-rays and gamma rays, as well as neutrons. Note that in general there are limited probabilities that the interrogating energy will interact with the target material and limited chances of detecting the return emission [NAV97] (we will have a brief look into the different factors of interest for the gamma ray spectrum in §2.3).

In the following we will give the priority to the physics behind existing systems or advanced prototypes. For additional interesting comments on bulk explosive detection see also [NAV97, McF80 and McF91, NAP98b].

### 2.1. X-ray Based Detection Systems:

High energy electromagnetic radiation is usually called X-rays or gamma rays according to how it has been generated (outside or inside the atomic nucleus respectively):

- **X-rays** are produced when electrons from outer orbits fall into a vacant inner orbit (typically produced when a fast electron hits an atom). Their energy is equal to the difference of the two energy levels involved (corresponding to the two orbits) and is usually expressed in units of **electron Volts (eV)**, whereby  $1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ Joule}$  = energy acquired by an elementary charge, such as an electron, when accelerated by a potential of 1 Volt. The X-rays useful for the detection of explosives have energies starting from several keV up to several MeV, i.e. wavelengths in the range  $10^{-8}$ - $10^{-11}$  cm. In fact there is no precise definition of the high-energy limit of the energy of X-rays (i.e. when to start speaking of gamma instead of X-rays), although about one MeV constitutes a reasonable separation.
- **Gamma ( $\gamma$ ) rays** are electromagnetic radiation of nuclear rather than atomic origin, and are produced as a consequence of nuclear reactions or radioactive decays. Their energy starts from about a hundred keV.

The absorption of an X-ray or  $\gamma$ -ray beam through a material is described by [YIN99]:

$$I = I_0 e^{-\mu l \rho}$$

where  $I$  is the intensity of the emergent beam (photons/s),  $I_0$  the intensity of the incident beam,  $\mu$  the total mass attenuation coefficient (describing both absorption and scattering) in  $\text{cm}^2/\text{g}$ ,  $l$  the length of path through the absorbing material (cm), and  $\rho$  the density of the absorbing material ( $\text{g}/\text{cm}^3$ ). The mass attenuation coefficient  $\mu$  depends on the energy  $E$  of the X-rays and on the effective atomic number  $Z_{\text{eff}}$  of the absorbing material;  $\mu$  decreases for increasing X-ray energy (the beam is less attenuated).  $Z_{\text{eff}}$  is, for a substance made up of more than one element, the apparent atomic number that results if the substance is treated as if it were composed only of a single element [NIJ99a]. It is closely related to the weighted average of the atomic numbers ( $Z_i$ ) of the constituent elements, i.e. to the average number of electrons per atom<sup>6</sup>.

In the case of X-rays their absorption is basically due to the X-ray's interaction with an atom's electrons, via the *photoelectric effect* (the X-ray is absorbed and knocks out one of the atom's internal electrons) or via *Compton scattering* (the X-ray hits an electron and transfers part of its energy to it, therefore continuing with reduced energy). Positron-electron *pair production* in the field of a heavy atom can occur at high energies, above 1.022 MeV.

All of the X-ray based systems involve irradiation of a target item with X-rays, usually followed by detection of an image created by X-rays that are either *transmitted*<sup>7</sup> or *backscattered*<sup>8</sup> by the item. **Standard**

<sup>6</sup> The atomic number  $Z$  of an element is equal to the number of protons in the nucleus of an atom of that element, and therefore to the number of electrons in the atom's shell (for a neutral atom).

<sup>7</sup> X-ray detector on *opposite* side to X-ray source.

(**transmission**) X-ray machines have been used for quite a long time, but more in the role of *systems to detect weapons and clues to the explosive device* such as switches, detonators, wires, etc., *rather than the explosive itself* [NIJ99a]. Standard airport X-ray machines operate with electron energies of 120 keV impinging on tungsten targets, and the resulting X-ray beam has the characteristic energy of tungsten (~60 keV) [YIN99]. Higher energy machines should be capable of penetrating a few cm (2-3) of steel, and even more for increasing energy.

In order to provide an operator with identification of explosives-like substances (**high density<sup>8</sup>, low Z material**), i.e. real bulk explosive detection, other X-ray technologies like backscatter, dual energy, or computed tomography and combinations thereof have to be employed. The parameter of interest is actually  $Z_{\text{eff}}$ , the effective atomic number of the screened item (replace in the following paragraphs Z by  $Z_{\text{eff}}$ ).

- **Backscatter** systems produce an image from X-rays that are scattered back from the screened object towards the source (not only transmitted as in the standard machines described above). Because low-Z materials are more efficient at scattering X-rays, explosive-like materials are more contrasted – they stand out clearly – in the backscatter image, while they often are barely visible in the transmitted image (low contrast). The backscatter image is indeed usually most effective for the detection of low-Z materials such as explosives, while the transmission image is most useful for viewing metals. Backscatter systems can display both the backscatter and transmission images. Quantitatively, a measure of the backscattered X-rays together with the standard absorption measurement provides information which can help in *separating the effects of density and effective atomic number  $Z_{\text{eff}}$* , in order to identify high density, low  $Z_{\text{eff}}$  materials (the signature of explosives).
- **Dual energy** X-ray systems yield superior material discrimination through comparison of the attenuation of X-ray beams at two energies. Thus, identification of low-Z materials can be achieved by using incident X-ray beams of two distinct energies. Materials of specific Z numbers (the same effective Z as explosives) can be clearly highlighted for the operator by adding colour to the image. A material that has a high Z number (metals) is often coloured green, while low-Z materials are coloured orange, and materials with the same Z as explosives are red (not to be confused with colorised images displayed instead of black and white ones on some standard transmission systems). The lower the X-ray energy, the better the discrimination power, but lower energy photons are strongly absorbed [YIN99].
- **Computed Tomography** (CT) is an even more sophisticated X-ray technique in which cross-sectional images (“slices”) through an object are numerically reconstructed from X-ray projections at various angles around the object. These cross-sectional images can be added together to produce a three dimensional image (as in medical CAT scans). Along with the three-dimensional image, the effective Z number is calculated and materials with the same Z number as explosives can be identified. For details see [YIN99, NIJ98].

Any system that can determine that low-Z materials are present can have an **automated alarm** function added. A number of (mostly American) commercial systems are for example listed in Table 6, page 32 of [NIJ99a]. Additional details on X-ray techniques can also be found in [NIJ98, NAV97].

These systems are mostly used for screening luggage, packages, mail, etc., and most of them are not easily portable. *A few are usable for EOD tasks, but not to detect the explosive directly, rather to get information on the object’s internal structure, which can already be very useful.* See also the comments in Annex A2.1, A2.2.

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<sup>8</sup> X-ray detector on *same* side as X-ray source

<sup>9</sup> Compared to similar innocuous material.

## 2.2. Elements of Neutron Physics and Properties:

Neutrons are electrically neutral particles and can therefore interact only with nuclei (and not with the atom's electrons for example), see also [GOZ96]. Because of the short distance action of nuclear forces even low energy neutrons can therefore still penetrate thick substances, which is needed for the application at hand: 1-2 cm of steel and 20-30 cm of earth should be feasible, although with increasing attenuation for increasing thickness.

The behaviour of neutrons in matter depends strongly on their kinetic energy. **Fast neutrons** interact preferentially via scattering and nuclear reactions (see below). The probability of reaction (cross section) for **slow neutrons** ( $E < 0.5$  eV, definitions vary) changes instead heavily from one element to the other and according to the neutron energy, and is determined by individual resonances which feature as peaks in the cross section plots. The latter can be very large, which indicates a high reaction probability at the corresponding neutron energy. **Thermal neutrons** are a special type of slow neutrons, whose kinetic energy distribution is in equilibrium with their surrounding (with a typical energy of 0.025 eV at room temperature). They move on irregular paths like a gas through matter, neither accelerating nor slowing down, scattering quite a number of times until they are absorbed (captured in the nucleus). In detail, neutrons can interact with matter in the following ways:

- **Elastic scattering** with nuclei (similarly to the collision of two billiard balls). The kinetic energy loss (speed loss) per collision depends strongly on the mass of the nucleus the neutron is hitting: if the latter is large, the incoming neutron will practically not lose energy<sup>10</sup>, if it is small (like for hydrogen) the incoming neutron can lose up to its entire kinetic energy. Hydrogen rich material such as polyethylene is therefore often used to slow down fast neutrons. Note that the target nucleus is not excited (i.e. stays in the ground state). The reaction is therefore of the  $X(n,n')X$  type<sup>11</sup>.

**Elastic scattering** dominates for **slow** neutrons.

- **Inelastic scattering** with nuclei: when the incoming neutron has a sufficient kinetic energy (usually  $> 100$  keV for heavy nuclei and  $>$  some MeV for light nuclei) it can put the nucleus being hit in an excited state, which decays in a very short time to its ground state (say less than  $10^{-12}$  sec), releasing the energy difference as a  $\gamma$ -ray of characteristic energy. The latter is also called a "**prompt**"  $\gamma$ -ray as it is emitted so shortly after the collision. The incoming fast neutron continues with a reduced kinetic energy. The reaction is therefore of the  $X(n,n'\gamma)X$  type.

**Inelastic scattering** dominates for **fast** neutrons.

- **Nuclear reactions** with the production of charged particles or additional neutrons, usually starting from a given energy (a threshold), often a few MeV<sup>12</sup>, as they "consume" energy which has to be taken from the incoming neutron's kinetic energy. A nuclear reaction has often as consequence an **activation** of the material, i.e. the nucleus which has been hit becomes radioactive. This radioactivity can be short lasting (e.g. milliseconds or seconds). If the nuclei decay emitting  $\gamma$ -rays, these will be called **delayed**  $\gamma$ -rays (in contrast to the prompt ones mentioned above). Examples are nuclear reactions of the  $X(n,\alpha)Y$ ,  $X(n,p)Y$ ,  $X(n,2n)Y$  type.
- **Neutron capture** does preferentially take place when the neutron has sufficiently low energy, i.e. for **slow** neutrons, and is particularly important for certain nuclei at one or more specific energies ("resonances"). The resulting nucleus can decay in a number of ways, according to the type of target nucleus and energy of the incoming neutron, including by emission of a **prompt**  $\gamma$ -ray, again characteristic of the target nucleus; this type of reaction is therefore of the  ${}^AZ(n,\gamma)A+1Z$  type.

Concerning the orders of magnitude of the physical processes involved, fast neutrons are thermalised (slowed down to thermal energies) on a  $\mu$ sec timescale, whereas neutrons diffuse on a msec scale [McF80].

<sup>10</sup> Think of a small fast ball hitting a large one nearly at rest.

<sup>11</sup> The following notation is used for nuclear reactions:  $X(\mathbf{a},\mathbf{b})Y$ , with  $\mathbf{a}$ =projectile particle,  $X$ =target nucleus,  $\mathbf{b}$ =emitted particle,  $Y$ =resulting nucleus. Particles of interest to us are neutrons (n), gamma rays ( $\gamma$ ), etc.

<sup>12</sup> Apart from some exceptions such as  ${}^{10}\text{B}$ ,  ${}^6\text{Li}$ ,  ${}^7\text{Li}$ ,  ${}^3\text{H}$ ,  ${}^{14}\text{N}$ .

Note that from a biological point of view thermal neutrons are less dangerous than fast neutrons (higher fluxes of thermal neutrons can be tolerated). Fast neutrons have a greater range in target materials and thus allow detection of larger and/or more dense volumes.

### 2.3. Gamma Spectroscopy Neutron Based Techniques:

There are several neutron-based techniques for detecting explosives in bulk form, see for example [GOZ96] for an overview of some neutron based inspection techniques as well as for the description of some prototypes or existing systems (at the time of writing). Among these we have in particular a class of systems relying on **gamma spectroscopy**, in which *the  $\gamma$ -rays resulting from the previously described interactions are characterised with respect to their energy and intensity*. We note in passing that the  $\gamma$ -ray spectra contain a wealth of information, in particular on the chemical elements of the substance under analysis, but not on its molecular structure. The  $\gamma$ -rays produced are also far reaching, being able to traverse the thicknesses involved in the task at hand (the better the higher their energy).

All systems of this type, such as Thermal Neutron Analysis (TNA) and Fast Neutron Analysis (FNA) as well as their derivatives, are composed of at least a *neutron source* to produce the neutrons that have to be directed into the target, and a  *$\gamma$ -ray detector* to characterise the outgoing radiation. The **neutron source** can be either a radioactive source or an accelerator, possibly *moderated* (exploiting hydrogen rich substances to slow down fast neutrons using elastic scattering):

- Typical **radioactive sources** are Californium-252 ( $^{252}\text{Cf}$ ), with a half-life of about 2.6 years (one  $\mu\text{g}$   $^{252}\text{Cf}$  produces about  $2.3 \cdot 10^6$  n/s), or Americium-Beryllium (AmBe), which produces neutrons via the  $^9\text{Be}(\alpha, n)^{12}\text{C}$  reaction ( $^{241}\text{Am}$  has a half-life of 458 years).  $^{252}\text{Cf}$  neutrons produced by spontaneous fission have a lower energy spectrum (average energy of 2.1 MeV, most probable energy of 0.7 MeV); this source is therefore more indicated to produce thermal neutrons.
- **Neutron generators** (small accelerators) can also be used as sources, usually either of the D-D (deuterium-deuterium,  $\text{D}(\text{D}, n)^3\text{He}$ ), or D-T (deuterium-tritium,  $\text{T}(\text{D}, \alpha n)$  type<sup>13</sup>; the first produce fast neutrons of 2.5 MeV, the second fast neutrons of 14 MeV. The  $^9\text{Be}(\text{D}, n)^{10}\text{B}$  reaction can also be used. The yield of a D-D generator is usually lower than that of a D-T by one to two orders of magnitude, but this might be (more than?) counterbalanced by a reduced background. Note that these generators do emit isotropically, i.e. in all directions ( $4\pi$ ). They can work in either a continuous mode, or in bursts (pulsed operation) as short as a few  $\mu\text{sec}$ . The D-D generator has the advantage of not containing any radioactive material, whereas the D-T contains tritium (which is radioactive) and this can complicate its acquisition and transport. Work is ongoing on different types of generator, such as the so-called plasma focus, which will be able to produce very short pulses (in the nsec range).

Radioactive **sources** have the advantage of being cheaper and smaller than accelerators, but can obviously not be “turned off”. They are more “portable” but have to be transported in special containers (for the shielding) and might require quite some paperwork, according to the actual source strength, as well as dedicated personnel; on the other hand it is true that they are routinely used in a number of applications. They have to be changed at regular intervals, say after one or two half-lives (e.g. max 5 years for the  $^{252}\text{Cf}$  one), which obviously matters only for those with a short half-life.

The **neutron generators** have reached quite reasonable sizes, still weighing several tens of kilograms, high voltage electronics included, and throughputs of  $10^8$  to  $10^9$  neutrons/s (for the smaller models). Prices start somewhere around 50 kCHF, but are more in the 100 kCHF range. The ability of pulsing them can be of great advantage in reducing the background signal, allowing for example to differentiate prompt from delayed  $\gamma$ -rays (which will occur after the pulse), or  $\gamma$ -rays due to inelastic scattering from those due to neutron capture of thermal neutrons. Nevertheless, detecting the  $\gamma$ -rays during the pulse can be difficult, depending on the detector and its electronics, in particular for intense pulses. They are commercially available from a few manufacturers such as SODERN in France, <http://www.sodern.fr/>, MF-Physics in the US,

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<sup>13</sup> Deuterium (D or  $^2\text{H}$ ), is a naturally occurring hydrogen isotope, whereas Tritium (T or  $^3\text{H}$ ) is beta radioactive with a half-life of about 12 years.

<http://www.mfphysics.com/>, Schlumberger in the US, <http://www.slb.com/emr/generators/>, and the Institute of Automatics in Moscow, Russia [RAN99] (plus possibly other Russian sources). Neutron generators are routinely used for other applications such as in the oil exploration industry. Lifetime might have been a problem in the past (currently several 1000 hours?).

*Thermal neutrons* have to be generated by slowing down (**moderating**) fast neutrons, as apparently there are no portable means of producing them directly. This process can strongly reduce (by 2 to 3 orders of magnitude) the effective neutron flux, i.e. with respect to what produced by the unmoderated source [VIE99].

Some form of **shielding** is usually employed, both to screen the detector (from the direct neutrons) as well as the environment and the operator. Nevertheless, in general a respectful distance has to be kept from the source when outside its protective (shielding) case, or from the generator when in use – depending on shielding, from several meters up to 10-20 m say! Note that for the most intense generators activation issues have been reported, i.e. it was preferable to wait a few minutes before approaching again the object under analysis.

The **gamma ray detector** is another key element of the system. According to the requirements its complexity can range from a simple counting device (registering only the amount of gamma photons) to the measurement of the energy (gamma spectroscopy, essential for chemical characterisation). When the emphasis is on energy resolution – the single spectral lines have to be identified as precisely as possible – the choice often falls onto a **HPGe** (High Purity Germanium) detector, which has an excellent energy resolution (adjacent spectral lines can usually be very well separated). HPGe has unfortunately the following disadvantages: it is very expensive, its efficiency decreases rapidly with increasing energy (and is in particular very low at the 10.8 MeV nitrogen thermal capture line), and it has to be cooled to low temperatures either cryogenically with liquid nitrogen or electromechanically. Speed might also be an issue. There are therefore situations in which other detectors are preferred, such as **BGO** (Bismuth Germanate) or **NaI** (sodium iodide) scintillators, which have a poorer energy resolution (individual spectral lines are “washed out”, resulting in overlapping peaks) but can work very fast (high counting rates). These detectors are also much more affordable and do not need cooling. Detector neutron damage might also have to be considered depending on the operating parameters (some detectors are available in “hardened” versions).

The **gamma ray spectrum** itself can be quite complex, according to the target material and the operating conditions (in particular for buried targets!). Amongst the factors influencing the signal of interest coming from the target object – i.e. the number of  $\gamma$ -rays which are recorded – we schematically have the following:

- The number of incident neutrons, depending on the source strength and characteristics as well as on the problem geometry (distance to target etc.), the attenuation/thermalisation on the way to the target and *within* the target (e.g. UXO steel wall thickness, moderator details, presence of soil), and the target properties;
- The cross section for the elements of interest (i.e. the probability of reaction, such as capture, and of the decay of interest), their abundance in the target;
- The number of  $\gamma$ -rays which arrive back at the detector, again depending on the problem geometry and attenuation on the way to the detector (e.g. UXO steel wall thickness, presence of soil);
- The detector efficiency (depends heavily on the detector type, its size, the  $\gamma$ -ray energy, the counting rate);
- The efficiency of the data acquisition system.

Concerning the omnipresent *background  $\gamma$ -ray spectrum* (i.e. in addition to the signal of interest coming from the target object), it is in part due to natural sources or neutron interactions in nearby materials or in the equipment itself. Other factors will be considered further on.

Most systems need **several minutes** to reach sufficient statistics to make precise statements. Some elements might be hard to detect due to neighbouring interference lines by other reactions (e.g. O, F, S), or because the

energy of the emitted  $\gamma$ -ray is low (e.g. As at 280 keV) and therefore more attenuated passing through the container's walls (in particular steel in the case of UXO).

**Software** is undoubtedly one of the key issues, in particular in presence of complicated spectra as is often the case when using fast neutrons for example, and might need extensive resources even if appropriate hardware is available. According to the system and the task at hand different modes of operations can be envisaged, ranging from the identification of single characteristic spectral lines (peaks) as good indicators for the presence of key elements (chemical weapons for example), to more elaborate spectral deconvolution solutions (extraction of individual peaks from a complicated spectrum).

Broadly speaking, we can define a few typical **modes of operation**, in increasing order of *overall system complexity*:

- **Level 1:** detect one or more characteristic elements of the substance at hand (**qualitative**). This is for example at the basis of TNA systems for the detection of **explosives**, which basically look for the presence of **nitrogen** (and hydrogen). Similarly, TNA systems are also employed for the analysis of **Chemical Warfare Agents (CWA)** relying on the detection of (some of the) typical key elements such as **Arsenic (As), Bromine (Br), Chlorine (Cl), Fluorine (F), Phosphorus (P), and Sulphur (S)** (see Table 3).
- **Level 2:** detect more than one (ideally all) characteristic element, i.e. carbon, nitrogen and oxygen (and hydrogen) for explosives, measuring their *elemental ratios* such as C/N or C/O (**semiquantitative**), or even their *elemental concentrations* (**quantitative**). This could allow to actually identify the substance under analysis. Whether this is really necessary depends obviously on the operational requirements.
- **Level 3:** as Level 2 but in three dimensions, i.e. dividing the volume under analysis in voxels (volume elements) and characterising each of them.

There is actually a **Level 0** scenario which consists in “easier” *indirect methods* such as detecting hydrogen and quantifying its amount. This can be done for example using simple neutron backscatter techniques (see Annex A1.1), and has been employed as a quick method to differentiate chemical munition from ordinary one (for well defined scenarios), or to detect explosive substances hidden behind doors, tyres, etc., in counterterrorism applications. Similarly, a simple TNA system is also available for the assessment of chemical warfare agents detecting only Chlorine (see Annex A1.3).

A list of *parameters* to be assessed in *operational conditions* could include the following:

- *Software* (end-user friendliness, robustness to unforeseen objects or geometries e.g. when using a library);
- *Security* aspects (radiation hazard);
- *Side effects* on detection/false alarm rate (e.g. due to the *soil*);
- *Minimal detectable mass*;
- *Effect of different inert substances* (in the case of UXO) as well as of explosive *mixtures*;
- Effect of *casing thickness* (minimal detection mass increases);
- *Detection rate vs. detection time*;
- Possible *activation* of target object, and dependence on target object itself;
- Influence of particular elements on the  $\gamma$ -ray spectra and possibly on the false alarm rate, for example because of neutron capture, or because of spectral lines competing with the ones of interest (see also the comments in the TNA section).

Amongst the *drawbacks of neutron based systems* we find usually system complexity and cost, radiation hazard, system weight (especially due to heavy shielding), power requirements. Depth of penetration also has to be carefully assessed in case of buried objects, as well as the minimum amount of detectable explosive.



Concerning the specific subject of *humanitarian demining*, the International Atomic Energy Agency (IAEA) in Vienna has quite recently started a Co-ordinated Research Project (CRP) on the *Application of Nuclear Techniques to Anti-Personnel Landmine Identification*. More information is available from the Scientific Secretary, Ulf Rosengard (email: ulf.rosengard@iaea.org, phone: + 43 1 2600 21753). The corresponding reports such as [IAEA99, IAEA00] are a useful source of information on nuclear explosive detection methods.

Table 4 summarises some of the nuclear reactions of interest for the detection/identification of explosives, to which we are going to refer in the following.

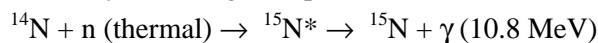
Element	Reactions	Neutron Energy	Reaction Type
H	${}^1\text{H}(n,\gamma){}^2\text{H}$	Thermal	Prompt
C	${}^{12}\text{C}(n,n'\gamma){}^{12}\text{C}$	Fast (>5 MeV)	Prompt
N	${}^{14}\text{N}(n,\gamma){}^{15}\text{N}$	Thermal	Prompt
N	${}^{14}\text{N}(n,n'\gamma){}^{14}\text{N}$	Fast (>3 MeV)	Prompt
N	${}^{14}\text{N}(n,2n){}^{13}\text{N}$	Fast (14 MeV)	Activation (9.9 min)
O	${}^{16}\text{O}(n,n'\gamma){}^{16}\text{O}$	Fast (>7 MeV)	Prompt
O	${}^{16}\text{O}(n,p){}^{16}\text{N}$	Fast (>9 MeV)	Activation (7.13 sec)
Cl	${}^{35}\text{Cl}(n,\gamma){}^{36}\text{Cl}$	Thermal	Prompt
Cl	${}^{35}\text{Cl}(n,n'\gamma){}^{35}\text{Cl}$	Fast (>3 MeV)	Prompt
Cl	${}^{35}\text{Cl}(n,p){}^{37}\text{S}$	Fast (14 MeV)	Activation (4.9 min)

Table 4: Nuclear reactions of interest for the detection/identification of explosives (source: [VAL99])

### 2.3.1. Thermal Neutron Analysis (TNA):

**Thermal Neutron Analysis** (TNA) determines the composition of target substances by measuring the results of the interaction of slow neutrons with matter (see also [BRO96]). At room temperature, these neutrons have an average energy of about 0.025 eV (thermal neutrons). The capture of such low-energy neutrons by a nucleus can result, as already discussed in §2.2, in the release of energy in the form of gamma radiation (“neutron capture  $\gamma$ -rays”).

TNA relies on the explosives’ elevated nitrogen concentration for their detection, as most of them are nitrated compounds whose nitrogen densities are above those of other materials. One interaction of particular interest is indeed the capture of thermal neutrons on **nitrogen**, following the reaction  ${}^{14}\text{N}(n_{\text{th}},\gamma){}^{15}\text{N}$ . The result of this interaction is the production, in about 18% of the cases, of characteristic 10.8 MeV  $\gamma$ -rays (the highest  $\gamma$ -ray energy produced from a naturally occurring isotope):



Nitrogen features also other spectral lines, but it is not clear if and how TNA systems exploit them at present. **Hydrogen** and most **metals** (e.g. iron for steel cased UXO) are also easily detected. The capture process on hydrogen produces deuterium (D or  ${}^2\text{H}$ ) with the release of a characteristic 2.223 MeV  $\gamma$ -ray following the reaction  ${}^1\text{H}(n_{\text{th}},\gamma){}^2\text{H}$ .

*In summary, TNA is able to characterise High Explosives (HE) by their nitrogen and hydrogen signature, possibly exploiting the absence of other elements as well. It is probably the “easiest” among the neutron-based techniques, apart from neutron backscatter. On the other hand it is relatively slow; typical response times range from minutes to tens of minutes, depending on the material being investigated. TNA it is not capable of detecting, in practical terms, neither oxygen nor carbon.*

In practice there are several obstacles to be overcome to apply TNA successfully for the detection of explosives:

- **Background reduction**, i.e. *how to extract in a reliable way the pure nitrogen signal*, which is, at 10.8 MeV, very characteristic but orders of magnitude weaker in intensity than the rest (the lower part of the energy spectrum) [GOZ96].
- *Possible Interference* from other elements: chromium, chlorine and nickel  $\gamma$ -rays have been quoted for certain applications [McF91], silicon (10.6 MeV line) if the object is buried (see also below). Copper and alloys containing it (e.g. brass) have also been mentioned.
- *Detector efficiency and/or energy resolution*: very unfortunately HPGe is rather inefficient at around 10 MeV. BGO detectors could have problems for this application due to a 10.2 MeV “internal” line coming from the reaction  $^{73}\text{Ge}(n,\gamma)$  in the detector itself.
- *Signal attenuation for buried objects*, and small signal to noise ratio when analysing *small masses*. For landmine detection for example the signal is influenced by burial depth, soil type and moisture content, sensor stand-off, and obviously explosive content (and to a small degree explosive distribution within the mine) [ANCxx1]. For buried objects in general the presence of boron or other rare earth elements can greatly increase neutron attenuation (because of their very high neutron capture cross section), thus reducing the depth at which the technique would work [SPA98].

As already indicated in §2.3, thermal neutrons have to be generated by slowing down (moderating) fast neutrons, as apparently there are no portable means of producing them directly. Concerning possible thermal neutron sources, the D-T generator is far from optimal for (pure) TNA as the 14 MeV neutrons are difficult to shield and produce quite some background. In addition, the moderation of 14 MeV neutrons to thermal neutrons is apparently quite inefficient<sup>14</sup>. D-D generators, or a radioactive source such as  $^{252}\text{Cf}$ , seem therefore to be more indicated if the aim is to generate a high number of neutrons in the thermal energy region.

Prototype TNA systems are or have been built by companies and organisations such as ANCORE Corp. (formerly SAIC Advanced Nucleonics until the end of 1997) [ANCxx1], Science Applications International Corporation (SAIC US, Santa Clara, CA) [SAI96, BOR00], SAIC Canada [McF98], the Italian INFN (National Institute for Nuclear Physics) EXPLODET collaboration [VIE99], etc. These systems have been mostly targeted at the detection of explosives for security applications, and also as confirmatory sensors for the detection of buried landmines.

A **prototype surface and near-surface UXO detector** based on TNA has been developed and demonstrated by SAIC [BOR00, ANCxx2, POR99]. It was composed of a Schiebel VAMIDS metal detector array and a TNA sensor head mounted on a remote controlled vehicle, and was tested during the summer and fall of 1996, in Socorro, NM, and at the Yuma Proving Ground, AZ, respectively. During this second occasion the system was fully integrated and capable of scanning, by remote control and with complete coverage, an area of 50x50 m in six hours. The TNA sensor head had a weight of about 150 kg, used a  $^{252}\text{Cf}$  radioactive source, and 8 NaI detectors in Socorro (5 minute measurement time) and 12 in Yuma (10 minute measurement time) [POR98].

[BOR00] summarises the results of these tests (as well as of landmine detection tests carried out with similar systems) as follows: “... large antitank mines and large ordnance items buried near the surface can be easily detected with nuclear radiation techniques under realistic field conditions. Smaller mines and UXO items can be detected under more ideal conditions.” It is also pointed out that this technique (as well as neutron backscattering) is affected by soil conditions, nonhomogeneity, and burial depth. A detailed analysis of the phenomena involved is carried out in [POR98, POR99, SPA98], including the effect on the signal to noise ratio of the interfering 10.6 MeV capture  $\gamma$ -rays from  $^{29}\text{Si}$  (which is in fact reported as being the dominant background source in the energy window of interest). The signal to noise ratio, reported to be of the order unity for the tested system, can remain challenging even after background subtraction.

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<sup>14</sup> Ed Waller, University of New Brunswick, *Private Comm.*, June 2000.

TNA has been successfully applied to the characterization of chemical warfare agents – it is in particular very sensitive to chlorine (see Annex A1.3) – by relying on the detection of characteristic elements, as already mentioned. Some of them are in fact better detectable by exploiting fast neutron inelastic scattering, for example phosphorus which has a thermal neutron capture reaction cross section a factor of 20 lower than chlorine [CAF92b §3.1, DOE92 p. 36].

### 2.3.2. Fast Neutron Analysis (FNA):

The **Fast Neutron Analysis (FNA)** technique measures the results of the interaction of fast neutrons with suspect matter, in particular *inelastic scattering* (i.e. reactions of the  $(n,n'\gamma)$  type) and the production of characteristic  $\gamma$ -rays as previously described. The neutron energy has therefore to be above a given threshold for each of the elements involved (see Table 4), about 5 MeV for *carbon* (producing characteristic 4.43 MeV  $\gamma$ -rays, with the corresponding energy peak apparently quite large<sup>15</sup>) and 7 MeV for *oxygen* (6.13, 3.84 MeV). *Nitrogen* can also produce intense high-energy  $\gamma$ -rays as a result of inelastic scattering with fast neutrons (at 1.63, 2.3 and 5.1 MeV for example).

As already mentioned in §2.3, the energies of the  $\gamma$ -rays emitted indicate the elements present in the material. The intensity of the  $\gamma$ -rays indicates the relative amount of material present. *It is therefore in principle possible to calculate the elemental ratios – how much of each element is present with respect to the others – in order to determine the type of substance under analysis.* In the instance of explosives, carbon, nitrogen, and oxygen ratios are considered. Hydrogen (i.e. the proton) cannot be detected by pure FNA.

FNA has therefore the potential of delivering better results than TNA, because it is *sensitive to nearly all elements in explosives* and opens the possibility of identifying the substance under analysis, but is usually far more complex and expensive. *The resulting  $\gamma$ -ray spectra can indeed be quite complex* as numerous nuclear levels are often excited, especially for 14 MeV neutrons hitting light elements, and even more in the case of buried objects (background due to soil<sup>16</sup>).

### 2.3.3. Pulsed Fast Neutron Analysis (PFNA):

Pulsed operations allow the use of timing information (e.g. coincidence or anticoincidence measurements<sup>17</sup>), and can be very useful for background reduction.

Pulsed operations are particularly interesting when using *very short fast neutron pulses* (typically nanosecond wide,  $10^{-9}$  sec) – short compared to the flight time across the object to be analysed. In addition, the neutrons have to be as monoenergetic as possible (they have to travel at roughly the same speed). Given these conditions, **Time-Of-Flight (TOF)** techniques can be used to determine the location of the detected material: the measurement start time is given when the neutron pulse is created, and the stop time when the  $\gamma$ -rays are recorded (the  $\gamma$ -rays travel at the speed of light, much faster than the neutrons). When combined for example with the vertical scanning of the neutron source and the horizontal movement of the object relative to the source/detector, pulsing provides a three-dimensional spatial resolution capability (still rather coarse but potentially very useful). The nature of the material is again provided by gamma spectroscopy.

Up to now this technique has required rather large installations to produce a neutron beam of the required characteristics (microsecond pulses have been routinely produced in commercial generators, but are obviously much longer than what required for TOF techniques), combined with the need for fast electronics and detectors. Work has been carried out in particular by the ANCORE Corp. (formerly SAIC Advanced Nucleonics, <http://www.ancore.com/>).

NOTE: The speed  $v/c$ <sup>18</sup> of a neutron of kinetic energy  $K$ , or actually of any particle, is equal to:

$$v^2/c^2 = 1 - m_0^2/m^2 = 1 - m_0^2/(m_0 + K/c^2)^2$$

<sup>15</sup> This can make calculations of the corresponding elemental ratios more difficult.

<sup>16</sup> Standard soils contain for example on average 50% of oxygen (as mentioned in §1.2).

<sup>17</sup> Activating for example the  $\gamma$ -ray detectors during brief intervals according to the timing of the neutron source.

<sup>18</sup> Speed measured with respect to the speed of light  $c$ , with  $c = 3 \cdot 10^8$  m/s =  $3 \cdot 10^{10}$  cm/s = 30 cm/ns.

where  $m_0$  is the particle rest mass (939.57 MeV/c<sup>2</sup> for a neutron) and  $m = m_0 + K/c^2$  is its relativistic total mass. A neutron with a kinetic energy of 8 MeV, for example, would therefore have a total mass of 947.57 MeV/c<sup>2</sup> (the c<sup>2</sup> is in fact usually dropped), and therefore a speed of  $0.13 \cdot c = 0.39 \cdot 10^{10}$  cm/s = 3.9 cm/nsec, i.e. 13% of the speed of light.

#### 2.3.4. Pulsed Fast-Thermal Neutron Analysis (PFTNA):

In a typical **Pulsed Fast-Thermal Neutron Analysis (PFTNA)** setup a neutron generator produces microsecond wide fast neutron pulses, e.g. 14 MeV neutrons from a D-T generator. During these pulses, and possibly also shortly thereafter, prompt  $\gamma$ -rays resulting from fast neutron inelastic scattering reactions (and nuclear reactions) are measured, in particular to identify carbon and oxygen. The accelerator is then kept off for a time of about 100  $\mu$ sec, and during this interval the neutrons thermalise and prompt  $\gamma$ -rays resulting from neutron capture reactions can be measured (in particular for the detection of nitrogen). The cycle then starts again. A longer pause can also be exploited (a few msec), in order to measure delayed  $\gamma$ -rays due to activation of one of the elements (such as oxygen).

The strength, as well as the weakness, of such a pulsed approach is that the signal to noise ratio improves, but that the overall signal strength is reduced by the duty factor of pulsing, requiring much stronger peak neutron intensity (to compensate for the low duty factor). This in turn can make the spectrum measurement during the pulse very difficult [GOZ96].

#### 2.3.5. Associated (Alpha) Particle – Time-of-Flight Neutron Analysis (API-TOF):

The **Associated (alpha) Particle technique** (or API, Associated Particle Imaging) uses an interesting property of the deuterium-tritium (D-T) reaction previously described, namely that the source emits a lower energy alpha particle simultaneously with, and at exactly at 180 degrees (“back-to-back”) to, each fast 14 MeV neutron produced. In a modified form of the D-T generator these alpha particles can be detected internally with a position sensitive detector, measuring their *time of generation* (and therefore that of the accompanying neutron) as well as their *direction relative to the source* (and therefore also the direction of the accompanying neutron, since its line of travel is opposite to that of the alpha particle). The fast neutrons thus produced are therefore also defined as “tagged” (by the associated particle), in time as well as in direction, which can lead to a significant reduction in background signal. The Associated Particle Sealed Tube Neutron Generators (APSTNG) Model A-910 and A-920 by MF Physics are examples of commercially available devices (<http://www.mfphysics.com/>, maximum output of  $10^9$  n/sec).

The neutron then collides with a nucleus and produces a  $\gamma$ -ray, as previously described, whose time of arrival at the detector can be precisely measured [NAV97]. This is therefore again a **Time-of-Flight (TOF)** technique as described in the PFNA section, allowing to determine the distance travelled by the neutron (as both the speed of the neutron and of the gamma are in principle known). As its direction is also known, three-dimensional spatial resolution of targets can in principle be provided, without the need for scanning. The nature of the volume element of material being analysed is again provided by gamma spectroscopy. Associated Particle Imaging is therefore a technique which can potentially provide 3D information (i.e. voxel by voxel) on the chemical nature of the object under analysis, ideally stoichiometric information (i.e. determination of the quantitative chemical formula:  $C_aN_bO_c$  for explosives, where a,b,c are atomic proportions<sup>19</sup>).

Note that the neutron production rate might have to be kept low so that neutron interactions do not interfere (need to limit random coincidences), depending on the detector and the electronics used; this would increase measurement time. Some of the neutrons will also lose part of their energy in collisions and therefore not be monochromatic any more, thus limiting system resolution. The need of having an extra detector built in the neutron generator does also not make things easier. This technique is therefore far from easy to implement outside of the lab. Research and development work has been or is ongoing for example at:

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<sup>19</sup> For example  $C_1N_2O_2$  for RDX, which is  $C_3H_6N_6O_6$ .

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

- Argonne National Labs (<http://www.techtransfer.anl.gov/techtour/lawenforce.html#Detection>, <http://www.re.anl.gov/apstng.html>); Brad Micklich <[bjmicklich@anl.gov](mailto:bjmicklich@anl.gov)>, Alexander De Volpi <[adevolpi@anl.gov](mailto:adevolpi@anl.gov)>) [SAL99].
- Consolidated Controls Corporation [MOL91, NAV97].
- “Atometer” collaboration at the DOE Special Technologies Lab in Santa Barbara, CA. Lead member: HiEnergy Microdevices, Inc. (<http://www.hienergymicrodevices.com/>, <http://www.nv.doe.gov/business/capabilities/FieldableProto/AssocPartImg.htm>); Bogdan Maglich <[maglich1@home.com](mailto:maglich1@home.com)>) [MAG00].
- The Joint Institute for Nuclear Research (JINR) in Dubna, Russia [BYS00].

### 2.3.6. Prompt Gamma Spectroscopy:

In a number of cases it is actually not necessary or appropriate to discriminate between TNA and FNA, stressing instead that **prompt**  $\gamma$ -rays are measured, independently of them being due to thermal neutron capture or fast neutron inelastic scattering. For example, in practice the neutrons used for TNA will also contain a fast neutron component, and therefore  $\gamma$ -rays due to their inelastic scattering reactions will be present in the spectrum together with the lines due to neutron capture (which is what one is looking for in pure TNA). Pulsed operations allow some degree of discrimination (see for ex. §2.3.4).

### 3. (Commercially Available) BULK Explosive Detection Systems:

A number of **bulk explosive detection systems of potential interest for the task at hand**, either commercially available or at the advanced prototype phase, have been identified. They will be described in the following pages, whereas Annex A1 will deal with other Explosive/Contraband detection technologies. Where possible comments are given on the following key aspects:

- **MATURITY (Market):**  
*How long has the product been on the market (including manufacturer data if available).*
- **AVAILABILITY:**  
*Off-the-shelf vs. (long) delay; special licence needed vs. general availability; local distributor vs. remote distributor, etc.*
- **COMPLEXITY:**  
*User education (training) level required; number of operators needed.*
- **MOBILITY:**  
*How mobile is the system (weight, fragility, etc.).*
- **INFRASTRUCTURE NEEDS:**  
*Time needed for possible preparations; clarify mobility needs, set up necessary infrastructure; need to meet legal regulations (e.g. radiation protection ordinance).*
- **OPERATIONAL READINESS:**  
*How quickly is the system ready (to make a measurement) in case of an alarm.*
- **DETECTION LIMITS & TIMES:**  
*E.g. grams, or ppm/ppb, and in which timeframe (“real time”, seconds, etc.).*
- **FALSE ALARMS (Rate):**
- **OTHER LIMITATIONS / (PERSONAL) COMMENTS:**  
*Note that comments are partly personal.*
- **PRICE.**

What we actually tried to do is comment in more detail two systems, PINS and PELAN, without repeating in detail all comments for the others, as many issues are similar (radiation hazard, cryogenics, etc.). Some references are provided for the reader's convenience, not all have been consulted. Arguments common to all (or most) of the systems include the following:

- All systems employing radioactive sources will probably need a license to deal with them (and perhaps also to transport them?).
- Need to use a *large detector* if relying on the 10.8 MeV nitrogen line (HPGe rather inefficient at that energy).
- *Systems will usually work best in reference situations (e.g. munition on a stand). Most of them have not been designed to characterise partially buried munition.*
- **PRICE:** It is rather difficult to get detailed price estimates, also bearing in mind that most systems are (advanced) prototypes or one-off copies. *In practice a price somewhere between 150 and 250 kCHF can be expected (say > 100 kUS\$).* The PRICE figure will therefore be mostly omitted in the following.
- **FALSE ALARMS:** Nearly no direct indications have been found on this issue. Some comments have already been provided in the sections describing TNA and FNA systems and their derivatives.

### 3.1. PINS – Portable Isotopic Neutron Spectroscopy (INEEL/Perkin Elmer, ex EG&G ORTEC):

**GENERAL DESCRIPTION:** TNA (+FNA), moderated  $^{252}\text{Cf}$  source (5  $\mu\text{g}$ ), HPGe detector.

According to official reports, the performance has been verified in the field in real-world situations by the US Army, which has successfully identified hundreds of suspect munitions from burial sites and firing ranges.

#### **MATURITY:**

Developed by EG&G ORTEC (now part of Perkin Elmer) and the Idaho National Engineering and Environmental Laboratory (INEEL) at the beginning of the '90s to determine in situ the specific nature of an assortment of containers of munitions and chemical weapons.

#### **AVAILABILITY:**

There have apparently been licensing problems a few years ago (difficult to export outside US), which are reported as having been solved. Delivery time quoted at 12 weeks.

#### **COMPLEXITY:**

Software seems to be reasonably user friendly. Moderate level of training/education probably required (computer, cryogenics, radiation safety,  $\gamma$ -ray spectra).

Two operators for work on the mother dewar (attaching and detaching the detector, etc.).

#### **MOBILITY:**

Portable system, can be operated up to 8 hours on internal batteries. Can be transported for field use. Shipped in 5 boxes with a total weight of 280 kg. HPGe detector must be filled with liquid nitrogen every 18 hours [*unless electromechanically cooled version employed!*].

#### **INFRASTRUCTURE NEEDS:**

When detector not in use, it should be attached to a 30-liter "mother" dewar which continuously refills it with liquid nitrogen (two-person team needed).

Detector must be used in a well-ventilated space ( $> 40 \text{ m}^3$ ), because in case of accident the 1.2 l of liquid nitrogen could expand to 800 l of gaseous nitrogen, displacing enough oxygen in a small room to cause asphyxiation.

Source must be stored after use in approved shipping container at least 5 m away from common human activity.

#### **OPERATIONAL READINESS:**

An uncooled detector requires at least 4 to 6 hours on the mother dewar before use. If the detector has been used and is still cold when attached to the mother dewar, it requires only 5 to 10 minutes to refill.

The HPGe detector is also available in an electromechanically cooled version (50x50x50cm compressor, needs mains connection or generator, at least in the version which was discussed; another version is described in [PAR99]).

#### **DETECTION LIMITS & TIMES:**

Typical sampling times: 100 to 1000 sec. 2000 sec recommended for HE (155 mm projectile!).

System should be able to identify: Chemical weapons, including nerve agents GA, GB (sarin) and VX; Blister agents HD, HN, HT (mustard gases), and Lewisite; High Explosives (HE) such as composition B, RDX and TNT; military screening smokes such as titanium tetrachloride (FM) and White Phosphorous (WP). **Practice munition filled with water, concrete or sand.**

PINS sensitivity is the highest for various smoke fills, followed by the CW agents that contain chlorine, and then by CW agents that contain phosphorous. PINS is least sensitive to explosive-filled items (the key element for their identification is N). Sensitivity is greater for large munitions as well as for thin-walled items (e.g. mortar projectiles) [PAR99].

**FALSE ALARMS (Rate):** TBD (TO BE DEFINED).

**OTHER LIMITATIONS / (PERSONAL) COMMENTS:**

Primary aim: chemical munition. Detection of HE via detection of H and N. *Sensitivity drops rapidly with detector-target distance.*

<sup>252</sup>Cf source can be used for two half-lives (5 years). About 3-5 m exclusion area around the source when in use.

HPGe detector is fragile, has to be handled with care. Detector, source and shielding are usually mounted on a stand for use. How to deal with munition in/on the ground (for the task at hand)?

Software: the *relative peak heights* (intensities), which are related to the ratios of the elements inside the target (i.e. their concentrations), are apparently also taken in consideration for the final decision-tree based evaluation (library of signatures?). Not clear which nitrogen lines are used.

**NOTE:** INEEL generally adapts the PINS software for new and unique situations (K. D. Watts, INEEL). INEEL is also currently developing a “mini-PINS” and a neutron accelerator based PINS.

**PRICE:**

Electromechanically cooled HPGe (as option): +30 kDEM.

**TESTING**

See References.

**REFERENCES:**

- [CAF92a] A. J. Caffrey, J. D. Cole, R. J. Gehrke, R. C. Greenwood, “Chemical warfare agent and high explosive identification by spectroscopy of neutron-induced gamma rays”, *IEEE Trans. On Nuclear Science* **39(5)**, pt. 1, pp. 1422-1426, Oct. 1992.
- [CAF92b] A. J. Caffrey, J. D. Cole, R. J. Gehrke, R. C. Greenwood, K. W. Krebs, “Portable isotopic neutron spectroscopy for nondestructive evaluation of CW”, in *Chemical Weapons Verification, Verification Technologies*, Department of Energy/Office of Arms Control and Nonproliferation, 1<sup>st</sup>/2<sup>nd</sup> Quarters 1992, DOE/DP/OAC/VT-92A (ref. [DOE92]), pp. 35-39.
- [COL93] J. D. Cole, M. W. Drigert, R. Aryaeinejad, A. J. Caffrey, “Nuclear physics in arms control: scenarios, techniques, and results”, in *Intl. Symposium on Nuclear Physics of our Times*, pp. 322-337, Sanibel Island, FL, Nov. 16-22, 1992. World Scientific, Singapore: 1993.
- [CAF94] A.J. Caffrey, *et al.*, “US Army Experience with the PINS Chemical Assay System”, INEL report EGG-NRP-11443, Sept. 1994.
- [PIN96] PINS Chemical Assay System, User’s Manual, Version 2.2, April 8, 1996, EG&G ORTEC.
- [PAR99] W. E. Parker, W. M. Buckley, S. A. Kreek, A. J. Caffrey, G. J. Mauger, A. D. Laviertes, “Portable system for nuclear, chemical agent, and explosives identification”, in *SPIE Proc. Vol. 3769*, pp. 43-50, Denver, CO, July 19-23, 1999.



### 3.2. PELAN – Pulsed Elemental Analysis with Neutrons (Vourvopoulos/WKU<sup>20</sup>, NUMAT):

**GENERAL DESCRIPTION:** PFTNA, pulsed D-T generator (MF Physics), BGO detector, deconvolution soft.

Specifically targeted for the application at hand (differentiating inert UXO from HE filled one). Probe setup – generator vs. detector position/orientation – is flexible.

**MATURITY:**

Different versions possible, systems starting to be commercialised. Some testing already done, some details in the References.

**AVAILABILITY:** About 8 months, export licence included (see also Testing).

**COMPLEXITY:**

Automatic operation via palm-top, from a distance up to 100 m from the probe. PELAN does not routinely display spectra to the operator.

**MOBILITY:**

Portable system, consisting of the Probe (20 kg, neutron generator head, BGO 3" x 3" detector, shielding), Power and Data Module (20 kg, low and high voltage controls, computer), and the palm-top-based Control. Special 10 kg platform provided, if required, for the PELAN-CW (chemical warfare) version. Can be transported for field use.

**INFRASTRUCTURE NEEDS:**

BGO detector does not necessitate cooling. Power requirements <100 W. System can operate from a shoulder held power pack (not provided) for at least 8 hours, or from a 110V/220V AC source.

**OPERATIONAL READINESS:** Set-up time of less than 1 hour.

**DETECTION LIMITS & TIMES:**

Minimal mass: 100 grams of explosives (expected; depends on casing thickness). Typical sampling times: 300 sec (up to 14 min for CW). Inert materials mentioned in the UXO tests: wax-based filling, or red epoxy filling.

**FALSE ALARMS (Rate):** TBD.

**OTHER LIMITATIONS / (PERSONAL) COMMENTS:**

Safety distance: larger than 7 m from the Probe [VORxx] (emitted radiation at 15 m is actually below the allowable radiation limits for general public). Neutron generator produces up to  $1.6 \cdot 10^8$  n/s isotropically.

Relies on advanced spectral deconvolution software (broad BGO spectrum with respect to the HPGe detector for example), based on a library of information; have apparently heavily invested in the software development. *If* the investigation is of same-sized objects under standard geometry conditions, an *absolute calibration* is possible, and the  $\gamma$ -ray counts correspond to a *specific elemental concentration*. When (as an opposite case) objects under *random conditions* have to be analysed, if the elemental contents cannot be uniquely determined from the number of counts of each element, *elemental ratios* such as C/O (up to 10% accuracy), C/N, and C/H are used in a decision making tree. These ratios are reported to allow the differentiation between explosives and innocuous materials, even when the explosives are hidden among other objects (e.g. tools in a tool box, clothing articles, various liquids, etc.).

Residual activation of ordinary materials is reported as minimal since for a 300 s interrogation of an object, neutrons are produced for only 10% of the time. Irradiation of foodstuffs can be calculated based on recent guidelines from the World Health Organization.

Note that an estimation of the *background spectrum* might have to be acquired via a measurement taken in the vicinity of the target, for example for objects lying on the ground. The **C/O ratio** is considered as primary. It is not perfectly clear which spectral lines are used for the determination of the nitrogen

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<sup>20</sup> Western Kentucky University (see also the References).

content, and how robust the system will be in unexpected situations (how much relying on library and geometry? Coping with mixtures?).

**PRICE:** > 100 K\$. Rights granted to a major corporation as from May 2001.

**TESTING**

The system was field tested in the USA with actual explosives (August 1999). Further testing is planned in Belgium and USA for chemical warfare agent identification (2001). See also the References.

**REFERENCES:**

“PELAN: Pulsed Elemental Analysis with Neutrons”, NUMAT, Inc. (brochure), 2000 (see NUMAT, Inc. Website: <http://www.numat.com/>).

[DEP98] L. Dep, M. Belbot, G. Vourvopoulos, S. Sudar, “Pulsed neutron-based on-line coal analysis”, *J. of Radioanalytical and Nuclear Chemistry*, Vol. 234, Nos 1-2 (1998), pp. 107-112.

[VORxx] G. Vourvopoulos, P. C. Womble, “Pulsed fast/thermal neutron analysis: A Technique for Explosives Detection”. <http://www.wku.edu/API/research/explo.htm>

[VOR99a] G. Vourvopoulos, “Method and portable apparatus for the detection of substances by use of neutron irradiation”, US Patent No. 5,982,838, Nov. 9, 1999.

[VOR99b] G. Vourvopoulos, P. C. Womble, J. Paschal, PELAN: A pulsed neutron portable probe for UXO, IED and landmine identification, in Application of Nuclear Techniques to Anti-Personnel Landmines Identification, Report of the First Research Co-ordination Meeting held 23-26 Nov. 1999 at the Rudjer Boškovic Institute in Zagreb, Croatia, IAEA publication IAEA/PS/RC-799.

Contact: [Ulf.Rosengard@iaea.org](mailto:Ulf.Rosengard@iaea.org).

[WOM99] P. C. Womble, G. Vourvopoulos, J. Paschal, P. A. Dokhale, “Multielement analysis utilizing pulsed fast/thermal neutron analysis for contraband detection”, in *SPIE Proc. Vol. 3769*, pp. 189-195, Denver, CO, July 19-23, 1999.

Western Kentucky University Web pages: <http://www.wku.edu/API/research/public.htm>

### 3.3. NIGAS – Neutron Induced GAMMA Spectrometer (Bruker Saxonia Analytik):

**GENERAL DESCRIPTION:** PFTNA, pulsed D-D generator, HPGe detector.

Targeted at Chemical Warfare Agents and Explosives, in particular via the identification of key chemical elements (for CWA: Arsenic, Bromine, Chlorine, Fluorine, Phosphorus, and Sulphur).

Similar in concept to PINS, replacing the radioactive source with a (unmoderated) D-D generator: about  $10^7$  n/s (2.5 MeV), pulse length 20  $\mu$ sec, pulse frequency 10 kHz. Max (overall) power consumption (when applying a liquid nitrogen cooled detector?): 800 W.

*Same comments as PINS concerning use of HPGe detector (will not be repeated).*

**MATURITY (Market):**

Starting to market the system for specific applications (esp. CWA).

**AVAILABILITY:** TBD

**COMPLEXITY:** User friendly software to identify single elements exists.

**MOBILITY:**

*TBD.* For the task at hand power requirements need to be carefully assessed. A jeep is necessary for transportation.

*(system portability might be an issue for the task at hand).*

**INFRASTRUCTURE NEEDS:** TBD

**OPERATIONAL READINESS:** TBD

**DETECTION LIMITS & TIMES:**

Typical sampling times: 300 sec (for CW). Probably much longer if the detection of nitrogen is required.

**FALSE ALARMS (Rate):** TBD.

**OTHER LIMITATIONS / (PERSONAL) COMMENTS:**

Primary aim: chemical munition.

IN pulse detection of P, S, As, F (prompt gamma due to inelastic scattering), OFF pulse detection of Cl, H, N (prompt neutron capture gamma). High detection efficiency due to the reduction of the interference between neutron capture and inelastically scattering reactions has been reported.

Are using D-D after initial experience with D-T (too high energy, D-D makes detection of the key elements just mentioned much easier). Accelerator developed in collaboration with a Russian company. Safety distance: 15 m from generator if no screening present, otherwise (with screening) about 2-3 m. Negligible activation of target object. Generator does not contain tritium.

Bruker has been clear about the non-optimal detection of nitrogen (the system cannot detect carbon nor oxygen, like PINS), i.e. long measuring times, in the standard configuration. Improvements/modifications of the system towards the detection of explosives are therefore under way. A special detector for the detection of nitrogen is being tested. In combination with the pulsed working regime of the generator (low background at the nitrogen gamma energy) good results for the detection of explosives are thus obtained.

Bruker suggested the possibility of **trying to identify the inert filler instead of the explosive** (when the possible fillers are known a priori), e.g. concrete from the characteristic Al and Si lines.

**PRICE:** TBD.

Likely to be quite high (with respect to PINS), according to the manufacturer due to the higher use value (e.g. D-D neutron generator). Transportation and storing costs are low because the neutron generator does not contain radioactive substances.

**TESTING:**

Real tests carried out with a number of chemical munitions (75 mm WWI shells), in collaboration with Tauber Spezialtiefbau GmbH (German EOD company), with positive results (see Refs.).

*REFERENCES:*

“NIGAS: The Neutron Induced Gamma Spectrometer”, Bruker Saxonia Analytik GmbH (brochure), 2000 (?).

“Zerstörungsfreie Identifikation von chemischen Kampfstoffen mit dem Analysensystem NIGAS” (Non-destructive Identification of CWA with the NIGAS Analysis System), Bruker Saxonia Analytik GmbH (report), 2000 (?), in German.

Web: <http://www.bruker-daltonik.de/>, [http://www.bruker-daltonik.de/company/ds\\_m.html](http://www.bruker-daltonik.de/company/ds_m.html), [sales@bsax.de](mailto:sales@bsax.de).

### 3.4. NIPPS – Neutron Induced Prompt Photon Spectroscopy (WIS/Hazard Control):

**GENERAL DESCRIPTION:** TNA + FNA, 3Ci AmBe source ( $8.1 \cdot 10^6$  n/s = 111 GBq; also accelerator), HPGe detector.

Targeted at Chemical Warfare Agents in particular. Developed by WIS (German Armed Forces Institute for Protection Technologies, Munster, Germany).

Similar in concept to PINS, using an AmBe source and somewhat *refined electronics* (dual ADC converters for high/low gain etc.). Developed own software.

*Same comments as PINS concerning use of HPGe detector (will not be repeated).*

#### **MATURITY:**

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#### **AVAILABILITY:**

Interesting system, which WIS does not sell; it has granted rights to a small company (Hazard Control). The latter made it in fact clear that A) the system still has to be ruggedised for field use, B) there is no market for individual units.

#### **COMPLEXITY:**

Software seems to be reasonably user friendly. Moderate level of training/education (computer, cryogenics, radiation safety,  $\gamma$ -ray spectra) probably required.

#### **MOBILITY:**

All parts and transportation boxes portable by 2 persons.

#### **INFRASTRUCTURE NEEDS:**

Source must be stored after use in approved shipping container...

**OPERATIONAL READINESS:** Set up time of less than 1 hour (if detector already operative).

#### **DETECTION LIMITS & TIMES:**

Typical sampling times: 1 to 30 min, depending strongly on the amount of agent present and the steel wall thickness of the container. About 10 min for a 155 mm shell.

No problem to detect H, Cl and As; for the other elements (P, S, F<sup>21</sup>), the detection sensitivity is lower and/or the detection is complicated by interfering gamma lines from other reactions. *The system is able to identify to some extent, with longer detection times, also C and O* (the neutrons produced by the AmBe source have a higher average energy than those from <sup>252</sup>Cf) and N.

**FALSE ALARMS (Rate):** TBD.

#### **OTHER LIMITATIONS / (PERSONAL) COMMENTS:**

Primary aim: chemical munition. Collaboration with OPCW inspectors. **HE not widely tested, nor (partially) buried objects.** Possible minimal explosive detectable mass of 1 kg (depends on steel casing thickness and geometry)?

The volume analysed by the system is estimated to be about a half-sphere of 10 cm radius centred around the detector surface.

**WIS suggested the possibility of using only BGO or NaI if the aim is only to detect nitrogen (more efficient at higher energies).**

**PRICE:** TBD.

#### **TESTING**

The DGA/DCE/CEB (Centre d'Études du Bouchet of the Délégation Générale à l'Armement, the French Defence Procurement Agency) has a NIPPS system available, which has been tested with positive results

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<sup>21</sup> One of the advantages of NIPPS is the detection of fluorine, which is not easy in particular when using Californium based systems.

[VET98] on WWI projectiles (1997). The latter are characterised by a lot of different geometries and compositions. The analysis of WWI munition is indeed not a simple task (wide number of configurations, several hundred different types, much testing was done at the time).

*Note that explosives were usually identified by the absence of P or Cl rather than by nitrogen detection (but “only” a 30% efficiency HPGe detector was used). Results do quite depend on the casing thickness.*

**REFERENCES:**

- [BUC96] F.-W. Buchholz, L. Schänzler, G. Tumbrägel, “Non-Destructive Evaluation (NDE) of Chemical Weapons: NIPPS”, German Armed Forces Institute for Protection Technologies – NBC-Protection (WIS-ABC), Munster, Germany, Sept. 1996.
- [VET98] F. Vettese, B. Asselineau, C. Pienne, F.-W. Buchholz, L. Schänzler, G. Tumbrägel, “Old Munition Identification by Neutron Interrogation Assessment of the German NIPPS System”, in Proc. 6<sup>th</sup> International Symposium on Protection Against C & BW Agents, Stockholm, 1998.

### 3.5. GIOS – Gerät zur Identifizierung Organischer Substanzen<sup>22</sup> (I.U.T.):

**GENERAL DESCRIPTION:** TNA +FNA or PFTNA, AmBe or pulsed D-T, HPGe or (larger) NaI detector.

Conceived as a modular system, with D-T generator or AmBe source, HPGe or NaI detector, different types of shielding, according to the exact needs.

Uses the portable (gamma) spectrometer NOMAD PLUS by EG&G ORTEC (now Perkin Elmer).

*Same comments as PINS concerning use of HPGe detector (will not be repeated).*

#### **MATURITY:**

A real commercial version does not exist yet. Part of the software would have probably to be modified or specifically written for the task at hand (the currently used software is a standard package from EG&G for the analysis of  $\gamma$ -ray spectra).

#### **DETECTION LIMITS & TIMES:**

Standard measurement time of 400 sec with D-T generator, but really depends on application.

#### **OTHER LIMITATIONS / (PERSONAL) COMMENTS:**

Safety distance: 10-20 m when generator in use, which probably produces up to  $10^8$  n/s, 12 Hz pulse repetition frequency, 1.5  $\mu$ sec pulse length (very intense pulses). Wait 10-15 min after the end of the measurement (activation of metallic objects!). AmBe radioactive source more indicated when thermal neutrons are required.

**PRICE:** TBD.

#### **TESTING**

I.U.T. has definitely practical experience in the analysis of munition and the discrimination of chemical vs. High Explosive (HE) vs. inert munition, *looking at a number of different parameters. The system was however operated by a specialist* (i.e. I.U.T. provided a service to Koch Munitionsbergungsgesellschaft mbH, a German EOD company). Some of the parameters which were looked at included the H/O vs. Si/O ratio (the inert shells were either empty, or contained concrete or silica sand), the oxygen peaks with respect to each others as well as their importance in the overall spectrum, etc. C/O, C/N ratios not considered up to now.

Other applications included the need to determine if a given substance was present or not in the object under analysis.

#### **REFERENCES:**

“GIOS: Gerät zur Identifizierung Organischer Substanzen”, I.U.T. (Institut für Umwelttechnologien) GmbH (brochure). <http://www.iut-berlin.de/>

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<sup>22</sup> Device for the Identification of Organic Substances.

### 3.6. NICEB – Neutron Interrogation by the Centre d'Études du Bouchet (DGA<sup>23</sup>/DCE/CEB):

*GENERAL DESCRIPTION:* PFTNA, pulsed D-T generator (SODERN), HPGe detector.

Targeted at Chemical Warfare Agents, in particular old WWI munition.

Similar in concept to the previously mentioned systems (e.g. GIOS), using a SODERN GENIE 16 pulsed D-T generator as source ( $2 \cdot 10^7$  n/s), and a “modified” NIPPS detection system.

*Same comments as PINS concerning use of HPGe detector<sup>24</sup> (will not be repeated).*

#### *DETECTION LIMITS & TIMES:*

Typical sampling times: 10 min.

#### *OTHER LIMITATIONS / (PERSONAL) COMMENTS:*

Primary aim: chemical munition.

The volume analysed by the system is estimated to be about a half-sphere of 10 cm radius centred around the detector surface.

**DGA does not sell/market the system itself. In the best case it can sell the technical specifications (how to assemble it).**

The detection of prompt  $\gamma$ -rays due to the impinging fast neutrons is carried out during the pulse, i.e. in coincidence with it, and is partially perturbed by the pulse itself (the detector is partially “blinded” during the neutron pulse). The detection of capture  $\gamma$ -rays, carried out in anticoincidence with the neutron pulse, profits on the other hand from a reduced noise level and features therefore a sensitivity higher than the one offered by radioactive source based systems<sup>25</sup>.

#### *TESTING*

System was tested by DGA/DCE (1998-99) on 50 WWI projectiles of different calibre, contents and origin (large variations are characteristic of WWI munition) with positive results [VET99]. A previous test on simulated 75 mm French projectiles (8 mm thickness) resulted in N and Sn being difficult to detect, and C quite impossible (all other elements of interest were easily identified), within the 10 minute measurement time.

*Conventional High Explosives munition has been identified by **an excess of oxygen** combined with the absence of key CWA elements. Direct identification using nitrogen detection, characteristic of HE, has been possible only in a few cases.*

The electronics could be improved (made faster), the software too.

#### *REFERENCES:*

[VET99] F. Vettese, P. Bourgeault, P. Bouteilloux, “Old Munition Identification by Neutron Interrogation – The French NICEB System”, in Proc. International CW Demil Conference (CWD99), Vienna, Austria, 7-9 June 1999.

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<sup>23</sup> Délégation Générale à l'Armement, the French Defence Procurement Agency.

<sup>24</sup> Apart from the fact that an autonomy of 5 days has been chosen for this system (the autonomy of the cooled HPGe detector does in fact depend on its cryostat's volume).

<sup>25</sup> F. Vettese, DGA/DCE/CEB, *Private Comm.*, Dec. 2000.



### 3.7. PNCAS – Pulse Neutron Chemical Analysis Sensor (EPPRA):

EPPRA is a spin-off of the École Polytechnique (Palaiseau, France) specialising in the development and supply of technology products to OEMs based on pulsed power and high energy plasmas. EPPRA has developed a novel technique for the detection of concealed explosives and is currently engaging in two EC projects relating to airport security and landmine detection (for humanitarian demining tasks). The *tomographic interrogation by neutron activation technique* promoted by EPPRA can be used to identify and remotely (non contact) locate the chemical composition of a buried object in situ. Basically, the aim is to tell which type of substance is buried where (with some approximation). Key to the system are a dedicated source (very short pulse plasma neutron generator) and a dedicated detector (large area very fast gamma detector).

The **Neutron Source** consists of a compact pulsed and ultra fast plasma neutron source. It is able to generate  $10^8$  high-energy neutrons (energy greater than 8 MeV) per 10 nanosecond pulse (pulses are very short!). The source is non-radioactive when switched off and has a low power requirement, less than 150 W. Time-of-Flight Analysis (TOF) is therefore also possible: it consists in measuring the time interval between two events, and therefore the particle's range – how far the particle has travelled – knowing its speed<sup>26</sup>.

Measurement of the outgoing  $\gamma$ -rays is carried out by a set of special purpose, low cost large area **gamma detectors**, with a very fast response time, less than 2 nsec. Measurements are concurrently possible over several different spectral channels (energy bands), and efficiency limiting pile up effects, due to two or more particles arriving too close in time, have been resolved by operating the detectors in current mode, instead of the traditional method of pulse counting.

In the end it is possible to obtain a distinct signature which characterises the elemental proportions – how much of each element (C, H, N, O) is present with respect to the others – in order to determine the substance type. This is implemented using novel data processing algorithms capable of extracting an explosive's features with only a few detection channels.

Locating the substance's position (in case of a buried object) should also be possible using triangulation methods, that is by knowing an estimate of the substance's distance along a direction and looking at the ground from several different directions.

[Source: EUDEM trip report, March 1999, Unpublished; revised Dec. 2000]

*Laboratory tests are foreseen for the end of 2000, with a prototype ready at the beginning of 2001.*

Web: <http://www.eppra.com/>

### 3.8. SODERN:

SODERN, France, has in fact all the necessary hardware to set up a system: D-T or D-D generators (one of the main manufacturers, with the basic unit – GENIE 16 – priced starting from around 360 kFF), detectors, high-speed electronics. The necessary software represents the crucial point, as it is usually developed only for specific applications having a real market potential (e.g. online cement analysis). A system could be set up for testing, but might have to be operated by a specialist.

Concerning similar applications, they have furnished D-T generators to INEEL (for PINS), the DGA for the analysis of chemical weapons (see the description of the NICEB system), and the French police.

Web: <http://www.sodern.fr/SODERN/neutronicsa.htm>

### 3.9. Other Prototypal Systems:

SAIC (US) has developmental programs [BOR00] which should result in commercial products in a few years' time. Their PIEDS system is similar to PELAN in concept and has been described in [HOL00].

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<sup>26</sup> 10 MeV neutrons travel about 4.3 cm in one nanosecond.

The potentialities of the “Atometer” API-TOF system by Maglich and colleagues [MAG00] are also acknowledged (see also §2.3.5); the system is however still in a development phase.

The use of a *time-tagged radioactive source* represents also an interesting development: a time trigger is provided when neutrons are emitted, which in laboratory tests allowed to reduce the background signal and enhanced the overall performance of a neutron backscatter system for landmine detection [CRA00].

### 3.10. Some Conclusions on BULK Explosive Detection Systems:

A few general comments can be made on the bulk explosive detection systems **described in this chapter**:

- All systems of interest revolve around *some form of gamma spectroscopy*, with different combinations of the neutron source, detector, electronics and software, often employing standard options (e.g.  $^{252}\text{Cf}$  radioactive source or D-T neutron generator, etc.). HPGe detectors have been used in the field but are somewhat fragile and need to be cooled (liquid nitrogen or electromechanically). All parts are important for a successful exploitation, including the *software* whose importance cannot be sufficiently stressed.
- The task at hand is rather specific and *the corresponding market therefore rather small* (at least up to now). *Most systems have probably not been sold up to now* (or in case as one-off copies tailored for specific tasks)!
- *PELAN seems to be one of the few systems specifically designed to characterise HE UXO*. All other systems have as primary aim the *identification of chemical munition* – a task where they seem to be working well, at least for verification purposes (e.g. checking stocks for compliance with international treaties) or when large quantities have to be destroyed (large installations) – or are not really portable.
- *The systems are not likely to have been tested on partially buried objects*.
- Most systems are likely to have problems for smaller pieces of munition. *Measurement times of several minutes have to be envisaged*.
- The EPPRA PNCAS system (see §3.7) has the potential of being in a class of its own whenever it will reach sufficient maturity. Systems based on API-TOF look also interesting on paper.

Basically, the following two approaches look possible<sup>27</sup> in the short term for EOD tasks:

- Detect explosives using a **TNA system**, i.e. **look solely for nitrogen** (and in particular the 10.8 MeV line) **and hydrogen**. This approach does in general preclude the possibility of identifying the explosive, unless some form of standard setup, and therefore calibration, is possible.

In this case a system such as **PINS** (Perkin Elmer) could be considered, probably with a large HPGe detector and a moderated californium source (the latter does anyhow probably represent the default). An alternative could be represented by **NIGAS** (Bruker), in which the presence of a D-D generator offers an interesting approach, perhaps with additional moderator material to increase the thermal neutron yield.

Improvements/modifications of the system towards the detection of nitrogen could also be envisaged, at hardware as well as at software level (use of a more efficient detector for example, e.g. larger HPGe or even NaI/BGO<sup>28</sup>, adaptation of current software, improved measurement setup). Note that in the case of PINS the possibility of adapting the existing software “for new and unique situations” has been explicitly mentioned by K. Watts, INEEL.

- **Detect other explosive constituents**, ideally all (**C, N, O and H**), using a (pulsed) neutron generator to produce fast neutrons. Sensitivity to nitrogen could on the other hand be reduced.

Most systems use D-T generators: **PELAN** (Vourvopoulos/WKU, NUMAT; BGO detector), **NICEB** (DGA/DCE; HPGe detector) or **GIOS** (I.U.T.; HPGe or NaI detector) which are unfortunately not available off-the-shelf.

An alternative is represented by the **NIPPS** system (WIS/Hazard Control) that employs an AmBe radioactive source (but the detection of oxygen is probably not easy given the energy spectrum).

**Radiation hazard** is obviously also present and will have to be dealt with.

<sup>27</sup> Conclusions partly based on discussions with F. Vettese, DGA/DCE/CEB.

<sup>28</sup> Lower energy resolution but higher efficiency at high energy.

## 4. TRACE Explosive Detection Technologies:

Trace explosive detection consists in the chemical identification of microscopic residues of the explosive compound, either in vapour or in particulate form (or both), whereby:

- **Vapour** refers to the gas-phase molecules emitted from the explosive's surface (solid or liquid) because of its finite vapour pressure, and
- **Particulate** refers to microscopic particles of solid material that adhere (contaminate) to surfaces that have, directly or indirectly, come into contact with an explosive material (see also §1.1.3).

A sample has therefore to be acquired and transported into the analytical device<sup>29</sup> (contrary to bulk detection in particular). Trace particle detection can potentially detect picogram-level samples of explosive material/ppt concentrations [NAV97, NAV9x]. Even lower sensitivities are certainly achievable, but whether for field systems remains to be seen. Note that the need for a field system does actually depend on the application: in at least one case, the Mechem MEDDS (Mechem Explosive and Drug Detection System, see §4.2.2), the sample is brought to the detector – dogs in this case! – for analysis. A list of different trace technologies and their acronyms is provided in Table 5. They are discussed in more detail in Annex A3.

Acronym	Detector Type
Colour	Colour Change of Test Paper
ECD	Electron Capture Detector
FIS	Field Ion Spectrometer
GC/CL	Gas Chromatograph / ChemiLuminescence
GC/ECD	Gas Chromatograph / Electron Capture Detector
GC/IMS	Gas Chromatograph / Ion Mobility Spectrometer
GC/MS	Gas Chromatograph / Mass Spectrometer
GC/SAW	Gas Chromatograph / Surface Acoustic Wave
IMS	Ion Mobility Spectrometer
ITMS®	Ion Trap Mobility Spectrometer (pat. Ion Track Instruments)
TR	Thermo-Redox

**Table 5: Trace explosive detection technologies and their acronyms (source: [NIJ99a], Table 3)**

### 4.1. Sampling:

With most commercial trace explosives detection systems, there are two common means of collecting samples: swipe (or particle, or particulate) collection and vapour collection. Some comments on particle collection have already been provided in §1.1.3. Other sources of information are [NIJ99b, NIJ99a, NAP99 Ch. 7]. Comments on sampling and preconcentration techniques are also provided in [YIN99, §2.3, McF80, McF91].

In **swipe collection**, a sampling pad (usually supplied by the manufacturer), usually paper or cloth [NIJ98], is wiped across a surface suspected of having residue of explosive material; direct contact is therefore required. This surface could be a tabletop, the outside of a package, a piece of luggage, clothing, and so forth. The sampling pad is then inserted into a sampling port on the instrument for thermal desorption and subsequent analysis. Particle detection is also discussed in some detail in [NAV9x, YIN99].

In contrast, **vapour collection** involves the use of a small hand-held vacuum cleaner to *collect airborne vapours or particles*. Typically, vacuuming is performed just above the surface to be investigated. A collection filter (or a pre-concentrator) is located inside the inlet of the vacuum, and air is drawn through this filter. The explosive material (actually in the form of either vapour or particles, see also [NAV9x]) will be trapped on the filter. The filter is then removed and analysed by the system in a manner similar to the

<sup>29</sup> Some exception exist, such as Fourier Transform Infrared (FTIR) trace detection, in which explosive residue on an exposed surface is analysed *in situ* with infrared light [NAV9x].

analysis of a swipe sample. Vapour sampling of this sort is generally less sensitive than swipe sampling, but is for example advantageous for screening people because it is not necessary to touch the person being screened (taking samples with vapour collection is regarded as less invasive than collecting swipe samples).

**Sample acquisition** is identified in [NAV97, NAV9x] as the *primary weakness* of current trace detection systems, rather than detector sensitivity, for the applications therein discussed<sup>30</sup>. See also [ROU97b]. An interesting discussion and critical analysis of vapour vs. particle explosive detection is also carried out in the [NAV9x] report.

Note that all trace gas detectors can be used with *preconcentrators*, which essentially act as gain amplifiers [McF91]. Their efficiency is somewhat constrained for practical applications by the need to keep a reasonable measuring time, in particular in the case of real-time systems. On the same topic see also [YIN99, McF80].

## 4.2. UXO/Landmine Characterization or Detection:

*Trace explosive detection technologies and the corresponding commercially available systems are rather mature, but mostly aimed at security (law enforcement) applications. We will consider them separately in more detail in Annex A3, and turn now our attention to the problem of **UXO characterization or detection**. The following general questions seem relevant in this context:*

- **Particle** detection: explosive particle contamination of the UXO surface might be possible, for example due to the production process, to storage or handling (similarly to what has been reported for landmines), or to firing of shells in the UXO's neighbourhood. At which level?

Note that the possibility of *cross-contamination* with other explosives cannot be excluded. An inert object could therefore still give a positive reading. The practical feasibility of collecting surface contamination is another important issue, e.g. when the UXO should not be touched.

- **Vapour** detection: Explosive vapours might leak from the UXO (e.g. through the fuse assembly?), especially from older munition likely to show signs of corrosion, or when the casing is broken. At which level?
- In the case of (partially) buried UXO, which would be level of **soil explosive contamination**? Would it make sense to analyse soil samples in the UXO's proximity (probably less likely to work in contaminated areas)?
- Can these parameters, which are a function – as is typical in trace explosive detection – of a large number of variables such as environmental parameters, the UXO's "history", etc., be translated into **operationally useful parameters**?

The detection of other substances, such as explosive degradation products or signature compounds (e.g. cyclohexanone, a solvent, associated to C-4), could also be considered.

Trace detection of UXO seems to be possible, at least in some circumstances, as application of dogs would seem to testify (for example during demining operations), so that the same might be true for their characterization (inert or not). However, we can anticipate that there does not seem to be a lot of material available on this subject, let alone a commercial system. We will therefore turn our attention to work in similar fields (e.g. landmine detection), as well as to some R&D work concerning more specifically the UXO problem.

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<sup>30</sup> The report's focus is on portable explosive detectors for technicians and security forces in the field.

#### 4.2.1. Estimates and Ongoing Studies in Related Fields:

Concerning the *detection of buried* artillery rounds, [McF80] estimates that, unlike mines, they are essentially hermetically sealed units having such high attenuation factors as to preclude detection by trace gas means.

Studies and measurements on **environmental fate and transport of explosives** are carried out mostly in relationship with landmine detection, for example at the Sandia National Labs, CRREL (USACE Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory), FOA (Swedish Defence Research Establishment), DRES (Defence Research Establishment Suffield, Canada) and probably others. MECHEM (South Africa) has also quite some experience on the subject.

This work tells us that *in the case of landmines some explosive vapour emission is indeed likely to occur* gradually from leaks in the casing or through seals and seams, and/or from evaporation of the residual explosive found on the surface of the casing [DES98]. The soil could also be contaminated with trace quantities of explosives during the burial process (but this looks less likely to be applicable to the scenario we are considering).

Detailed results of modelling activity are for example described in [PHE98, GEO99, WEB99]. It is particularly interesting that *explosive compounds such as TNT, DNT and RDX will have (for the given assumptions) over 90% of the mass fraction adsorbed to the soil solid phase*, up to 10% present in the soil aqueous phase, and less than  $10^{-6}$  in the soil vapour phase. The effect of parameters such as burial depth, how long the mine has been buried (time lag), biochemical half-life of explosives<sup>31</sup>, location and climatic conditions, uptake by plant roots, soil moisture, etc., have also started to be addressed.

The *importance of 2,4-DNT and 1,3-DNB vapours* (explosive related chemicals) for the detection of landmines has also been stressed, as *they can be majoritary with respect to (2,4,6-)TNT* [GEO99]. Some authors estimate the concentration of TNT in air over a landmine as being a factor  $10^3$ - $10^6$  below the equilibrium vapour concentration, which would mean *ppt* (part per trillion,  $1:10^{-12}$ ) to *ppq* (parts per quadrillion,  $1:10^{-15}$ ) sensitivity necessary to detect TNT in the vapour phase (!).

Providing realistic figures for explosive vapour concentrations is indeed not easy, as the vapour losses are difficult to estimate. For comparison, in the case of IEDs [McF91] quotes a “crude” upper limit of  $1 \text{ ng/m}^3$  ( $\text{m}^3$ , not  $\text{cm}^3$ !) for the minimum sensitivity necessary to detect TNT (which would be about a factor  $10^5$  lower than what expected from the vapour pressure alone, corresponding to 0.1 ppt). The most sensitive technique quoted in the same report was atmospheric source mass spectrometry, in particular APCI MS (Atmospheric Pressure Chemical Ionization Mass Spectrometry). It was deemed sufficiently sensitive even without the use of preconcentrators, whereas atmospheric source tandem mass spectrometry (MS/MS) was deemed marginally feasible without preconcentrators and feasible with one, and IMS was deemed feasible with a preconcentrator. All estimations were based on the previously quoted limit. A number of other studies have been certainly carried out since.

*Sample acquisition* is again a key issue. Improved sampling devices have been proposed [YIN99], for example in [FIS98] for particles, in [CHR99, GEH99, GEI99] for vapours. Building soil probes to extract the explosive compounds adsorbed on soil particles and/or dissolved in the soil water is also an attractive option, if operationally feasible.

In 1997 the US Defense Advanced Research Projects Agency (DARPA) started a 3-year technology development program to detect mines via their chemical signature (“Dog’s Nose Program”). The results of these extensive efforts are detailed at <http://www.darpa.mil/ato/programs/uxo/>.

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<sup>31</sup> Estimated for example at about 1 year for TNT and 36 years for RDX from LANL (Los Alamos National Labs) Long Term Surface Soil Tests [PHE98].

#### 4.2.2. Practical Applications:

**Dogs** are being used in humanitarian demining for the detection of landmines as well as UXO (depending on which type they have been trained on, probably mostly surface items or shallowly buried ones), see for example [HOR98], also for a description of the Mechem MEDDS (paper #6), and [LJU99]. Detection of UXO only has also been reported. Within MEDDS one actually distinguishes between so-called “chemical dogs”, which are trained to smell pure chemicals such as TNT or RDX, and “bouquet dogs”, which are trained to recognise composite smells (e.g. from a given plastic mine) in which the explosive might not necessarily be dominant (the plastic or rubber component of a landmine or metal of an UXO might be). *In this last case landmine/UXO detection is therefore not necessarily synonymous with explosive detection.*

The **Sandia National Labs** have carried out work with the objective of **developing a field portable chemical sensing system to examine mine-like objects and UXO in near-real time**. Field tests have included unearthed mortar rounds and artillery shells, and AP/AT mines on land [ROD00]. One sampling system was designed for soil vapour sampling, another for sampling exposed munitions, the latter consisting of a battery-powered pump and a short quartz tube; the explosive is then thermally desorbed into an Ion Mobility Spectrometer. The chemical sensing systems are capable of sub-ppb detection of TNT and related explosive compounds.

**UXO exposed to the environment was analysed** to determine whether they were inert or contained explosives (July 1998, Cape Cod, MA): a total of 1112 projectiles, including 60 mm mortars, 81 mm mortars, and 105 mm artillery shells were analysed, along with 151 pieces of scrap ordnance, partial fuses and other items. The UXO showed a significant amount of corrosion. *The samples were collected along seams, joints, and where breaches in the case could be observed.* As most shells were expected to be inert, they were analysed in groups of 25, with a sampling time of 125 seconds per group. If a signal was observed, the shells in the corresponding grouping would be re-analysed individually. All 1263 items were sampled in three days.

Every shell was cut open to verify the contents. Overall the vast majority were found to be inert. The vapour analysis did not produce any false positives (i.e. false alarms), but two false negatives (two intact 105 mm shells which were found to be live and for which no IMS signal was registered, for unknown reasons). Additionally, ten 105 mm shells believed to contain explosives were analysed at Sandia. All produced detectable signals and were correctly identified. For details on the landmine field tests see also [CHA99]. They allowed to prove the ability to detect explosive molecules in soil samples in the vicinity of buried land mines.

**INEEL** (Idaho National Engineering and Environmental Laboratory)<sup>32</sup> has carried out tests on new munitions at Dugway Proving Grounds to *determine if explosive vapours could be detected outside them. Explosives were not detected using IMS technology.* INEEL continues to develop methods to sense very low levels of explosive vapour near munitions.

[INEEL is also developing a mobile Secondary Ion Mass Spectroscopy (SIMS) system for the detection of trace chemicals on surfaces, with a system being currently deployed on an Army’s system and undergoing evaluation. Laboratory based SIMS systems are currently used at INEEL to detect very low levels of chemicals on surfaces. Explosives are more difficult to detect than chemical warfare agents. SIMS has been tested at the Army’s facilities at Dugway Proving Grounds. SIMS can be optimised for explosives detection.]

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<sup>32</sup> Kenneth D. Watts, INEEL, *Private Comm.*, June 2000.

## 5. Conclusions:

We recall that the **main goal** of this study was to *characterise existing technologies, and identify corresponding commercially available systems, for the direct detection of explosives for Explosive Ordnance Disposal (EOD) tasks. Systems should be able to determine if a given piece of munition, which has already been detected by other means, contains explosives or is inert, and ideally in the former case to establish the type of explosive.* It was in fact agreed to keep the target application and audience somewhat larger at the beginning of the study (see the Introduction). As a result, explosive detection systems which are not necessarily directly applicable to EOD tasks have also been studied and described, mostly in the Annex.

We can summarise our findings as follows:

- **Bulk** explosive detection: the quantity of explosive is rather well known for UXO (say above 100 grams), partly also in the case of IEDs (e.g. airport security). The range of explosives is not necessarily the same for UXO and IEDs.

*Systems capable of direct bulk explosive detection<sup>33</sup> seem to still have quite a way to go, apart from advanced X-ray based systems used for screening luggage, packages, mail, etc., most of which are not easily portable, and possibly some Thermal Neutron Analysis (TNA) sensors (level of diffusion unclear, see also Annex A2.2).*

**UXO:** Systems exploiting low frequency electromagnetic fields (NMR, NQR) are probably useless for the characterization of UXO due to shielding. This leaves at present only systems *using neutron sources and relying on gamma spectroscopy* as potential candidates (see also the corresponding Conclusions in §3.10, which will not be repeated in detail). Unfortunately *most of such systems have been designed for other tasks, such as the discrimination of chemical weapons.*

*Nearly no such system is as yet really available off-the-shelf, perhaps apart from PINS, and capable of working under all the assumptions listed in the Introduction. It should nevertheless be possible to identify one or more systems meeting most of the requirements.*

“Simple” bulk detection systems such as neutron or gamma backscatter, already used for security applications, could perhaps also be useful in selected scenarios.

Note that some degree of screening of TNA systems might be possible by using material with a high neutron capture cross section (e.g. boron, gadolinium, see also §2.3.1). On the other hand characteristic spectral lines would be produced, which might in turn be detected.

- **Trace** explosive detection: large number of possibilities and scenarios exist, also concerning the explosive source itself, which is not necessarily the target object (e.g. on a former battlefield). Large influence of environmental parameters, target history, etc., on the variables of interest (explosive vapour and particle concentration). Again, the range of explosives is not necessarily the same for UXO and IEDs.

*Trace explosive systems for security (law enforcement) applications, e.g. detection of IEDs, are mature and in current use. They usually have the capability of indicating the type of explosive. Some authors have identified *sample acquisition* as the primary weakness of current systems, rather than equipment sensitivity.*

Note that US public documents such as the NAP publications, the NAVEODTECHDIV reports, or the NIJ reports, are in general quite open in the discussion of (trace) explosive detection systems.

**UXO:** Reliable and consistent trace explosive detection is far from easy. Operationally useful parameters for UXO are difficult to quantify. R&D work is ongoing, including explosive environmental fate and transport modelling, in particular for landmine detection. Sampling is again of primary importance, and soil sampling is an option. Prototype systems have been used to characterise exposed munitions; explosive molecules in soil samples have

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<sup>33</sup> Not indirect via simple indicators such as the hydrogen concentration for example.



also been successfully detected (in the vicinity of landmines). Dogs are being used in humanitarian demining also for the detection of UXO (§4.2.2).

In the Introduction we remarked that at first sight bulk explosive detection would seem to be most appropriate for hermetically as well as some non-hermetically sealed systems, whereas trace detection would seem to be most appropriate for non-hermetically sealed systems. This is probably still true but perhaps too simplified a statement. For example, even for a perfectly sealed object explosive traces can be present on the surface (which is actually rather difficult to avoid) making it detectable. On the other hand, non-hermetically sealed objects can contain explosives with very low vapour pressure (volatility), making their vapour detection very difficult (although one might look for impurities, explosive decomposition products or other accompanying substances, e.g. for landmines).

Bulk detection is interesting on paper but far from being easy to apply in practice, in particular when looking for small quantities hidden in a complex matrix, with possible interferences being present as well. Neutron based systems are hampered by radiation hazard, NMR/NQR devices are screened by metallic enclosures. Detection times can also be too long to be practicable, depending on the application.

## **6. Acknowledgements:**

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#### **Web:**

SANDIA (National Laboratories) Online Technical Library: <http://infoserve.sandia.gov/>

#### **Institutions/Organisations carrying out R&D:**

A number of institutions carrying out trace explosive detection research, and with which it might be worthwhile to stay in contact, have already been mentioned in §4.2.1 and §4.2.2.

The **DGA** (Délégation Générale à l'Armement, the French Defence Procurement Agency) has been working to understand the potential of neutron based systems for the characterization of chemical weapons (F. Vettesse <[frederic.vettesse@etca.fr](mailto:frederic.vettesse@etca.fr)>, DGA/DCE/CEB). DGA/SPART (Service des Programme d'Armement Terrestre) has launched in the year 2000 an invitation to tender concerning a "Feasibility study for a landmine confirmation system based on neutron interrogation".

The EOD requirements of the **NAVEODTECHDIV** (Naval Explosive Ordnance Disposal Technology Division, Indian Head, Maryland) are probably quite similar to those of other Institutions/Organisations, e.g. <sup>35</sup>:

- *UXO*: Confirmatory sensor for fill. *Discriminate between inert, explosive and other fills.*
- *IEDs*: *Go/no-go gage.* Assist in disruption/render safe mission.

#### **BULK Expl. Detection of Landmines and/or UXO:**

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Contact: Douglas Brown <[doug@ancore.com](mailto:doug@ancore.com)>.

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## 8. Websites:

A list of selected Websites of interest follows (as always, not all-inclusive).

### IED (Improvised Explosive Devices)

IEDD - Improvised Explosive Device Disposal

<http://www.pwallen.co.uk/iedd/index.html>

Equipment Manufacturers and Distributors

<http://www.bombsecurity.com/eqmflist.html>

Bombsecurity.com: The Internet's Largest Source for Information on Bomb Related Protection Issues

<http://www.bombsecurity.com/index.html>

SAIC's Center for Counterterrorism Technology & Analysis

<http://www.saic.com/gov/cctta/>

### X-RAY Systems (esp. portable)

Golden Engineering

<http://www.goldenengineering.com/>

MinXRay, Inc.

<http://www.minxray.com/>

SAIC: Products: Safety & Security

<http://www.saic.com/products/security/>

Vidisco Ltd.

<http://www.vidisco.com/>

OTHER X-RAY Systems

PerkinElmer Instruments / Detection Systems Formerly EG&G Astrophysics, formerly

Vivid Technologies, Inc

<http://www.eggastrophysics.com/main.htm>

### BULK Explosive Detection/ELECTROMAGNETIC

#### NMR (Nuclear Magnetic Resonance)

SwRI Patent: NMR Discrimination Apparatus and Method Therefor

<http://www.swri.org/8special/patents/4166972.htm>

SwRI Patent: Baggage Inspection Apparatus and Method for Determining Presences of Explosives

<http://www.swri.org/8special/patents/4514691.htm>

### BULK Explosive Detection/NUCLEAR

Landmine Detection: The Problem and the Challenge

<http://www.unb.ca/ME/LTMD/LANDMINE.htm>

LTMD Homepage (Laboratory for Threat Material Detection)

<http://www.unb.ca/ME/LTMD/>

### API (Associated Particle Imaging)

DOE/NV - Capabilities: Associated Particle Imaging

<http://www.nv.doe.gov/business/capabilities/FieldableProto/AssocPartImg.htm>

HiEnergy Microdevices

<http://www.hienergymicrodevices.com/>

ANL / APSTNG (Argonne National Labs)

Argonne - Law Enforcement Capabilities

<http://www.techtransfer.anl.gov/techtour/lawenforce.html>

APSTNG System

<http://www.re.anl.gov/apstng.html>

### Gamma backscatter (esp. portable)

John Caunt Scientific Limited

<http://www.pq62.dial.pipex.com/>

John Caunt Scientific Limited

<http://www.johncaunt.com/>

SAIC: Products: CDS-2002i(tm) Contraband Detector: Overview

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

[http://www.saic.com/products/security/contraband\\_detector/cds.html](http://www.saic.com/products/security/contraband_detector/cds.html)

Background info

2 Background

<http://ifp.uni-muenster.de/~balla/thesis/background.html>

Bicron: Organic Products

<http://www.bicron.com/notegauging.htm>

### **NIGAS (Neutron Induced Gamma Spectrometer)**

Bruker Daltonik - Company Info

<http://www.bruker-daltonik.de/companies.html>

### **ORNL (Oak Ridge Nat. Labs)**

WEAF Research and Development

<http://www.ornl.gov/armd/r&d.htm#CPNX>

### **PELAN (Pulsed Elemental Analysis with Neutrons)**

Detection of Explosives (WKU Applied Physics Institute)

<http://www.wku.edu/API/research/explo.htm>

NUMAT, Inc.

<http://www.numat.com/>

Publications (WKU Applied Physics Institute)

<http://www.wku.edu/API/research/public.htm>

### **PINS (Portable Isotopic Neutron Spectroscopy)**

ORTEC PINS Chemical Weapons Assay

<http://www.eggortec.com/pins.htm>

ORTEC PINS Chemical Weapons Assay

<http://www.ortec-online.com/pins.htm>

Securing the Future at INEEL

<http://ineext1.inel.gov/science/feature.nsf/ineel/Secure>

PINS technology identifies chemical weapons

<http://ineext1.inel.gov/science/feature.nsf/ineel/pins>

### **PNCAS (Pulse Neutron Chemical Analysis Sensor )**

EPPRA: European Pulsed Power Research

<http://www.eppra.com/>

### **SODERN**

Sodern neutronic, neutron generator, online analyser

<http://www.sodern.fr/SODERN/neutronicsa.htm>

### **OTHER BULK/NUCLEAR**

SNUPA (Slow Neutron Universal Parcel Analyser)

The University of Melbourne - School of Physics - Photonuclear Research Group

<http://www.ph.unimelb.edu.au/photo/>

### **CONFERENCES**

2000 GRC (Gordon Research Conferences) on Illicit Substance Detection

<http://www.grc.uri.edu/programs/2000/illicit.htm>

WKU - Crete 2000--International Conference on Explosives and Drug Detection Techniques

<http://www.grc.uri.edu/programs/2000/illicit.htm>

### **OVERVIEW RESOURCES**

Federal Remediation Technologies Roundtable

<http://www.frtr.gov/topical/uxo/index.html>

Explosive Detection Equipment Program / US Navy

See "Tech Info Library" and "EDE Catalog -> Catalog, Survey, Vendor List"

(<http://www.explosivedetection.nfesc.navy.mil/>)

Justice Information Center (NCJRS): Research and Evaluation Documents



## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

Look for "explosives" (twice -> "Guide for the Selection of Commercial Explosives Detection Systems for Law Enforcement Applications")

(<http://www.ncjrs.org/resdocs.htm>).

Sandia National Laboratories Technical Library Homepage

<http://infoserve.sandia.gov/index.html>

UXOCOE (UXO Center of Excellence) Workshop Notes -> NVESD/JUXOCO Explosive Detection Workshop (25-27 Aug 99)

(<http://www.uxocoe.brtrc.com/workshp.htm>)

UXOCOE (UXO Center of Excellence) TechReports

<http://www.uxocoe.brtrc.com/TecReports.htm>

### *Chemical & Engineering News*

C&EN, Detecting Illegal Substances, September 29, 1997

<http://pubs.acs.org/hotartcl/cenear/970929/detect.html>

C&EN 970310 - LAND MINES: Horrors Begging for Solutions, March 10, 1997

<http://pubs.acs.org/hotartcl/cenear/970310/land.html>

C&EN, Government, Industry Efforts Yield Array Of Tools To Combat Terrorism, July 24, 1995

<http://pubs.acs.org/hotartcl/cenear/950724/art02.html>

### *Nat'l Academy Press*

Nat'l Acad Press Catalog: Assessment of Technologies Deployed to Improve Aviation Security: Assessment of Technologies Deployed to Improve Aviation Security: First Report, 1999

(<http://www.nap.edu/catalog/9726.html>)

Black and Smokeless Powders

Black and Smokeless Powders - Technologies for Finding Bombs and the Bomb Makers, 1998

(<http://books.nap.edu/html/smokeless/>; also: <http://stills.nap.edu/html/smokeless/>)

Nat'l Academy Press, Containing the Threat from Illegal Bombings: (1998), Front Matter

Containing the Threat from Illegal Bombings: An Integrated National Strategy for Marking, Tagging, Rendering Inert, and Licensing Explosives and Their Precursors (1998)

(<http://books.nap.edu/books/0309061261/html/R1.html>)

### OTHER literature

Justice Information - National Criminal Justice – Research and Evaluation

<http://www.ncjrs.org/reshome.htm>

Startseite Büro für Altlastenerkundung und Umweltforschung Dr. Rainer Haas

Reference documents on explosives (in German)

(<http://haas.purespace.de/start.html>).

### **TRACE Explosive Detection**

Barringer Technologies Inc.

<http://www.barringer.com/>

Electronic Sensor Technology Intro Page

<http://www.estcal.com/>

Explorer 2000 / NUSS

<http://www.via.at/explorer2000/>

Explosive Detection Equipment or Services

[http://www.pseag.org/CWG\\_Products/Explosive%20Detection%20Equipment%20or%20Services\\_1.html](http://www.pseag.org/CWG_Products/Explosive%20Detection%20Equipment%20or%20Services_1.html)

Graseby Dynamics Limited - A Member of Smiths Industries Aerospace Group

<http://www.grasebydynamics.com/>

IDS Intelligent Detection Systems

<http://www.idsdetection.com/>

IDS Analytical + Security Division

<http://www.tracedetection.com/>

Ion Track Instruments

<http://www.iontrack.com/>

I.U.T. GmbH

<http://www.iut-berlin.com/>

MSA Instrument Division - Permanent Instruments - FIS Project

<http://www.msanet.com/instruments/ps/permanent/fis/index.htm>

Nomadics, Inc. - Portable sensors and wireless solutions for the future

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

<http://www.nomadics.com/>

Thermedics Detection Inc. Web Site Intro Page 1

<http://www.tdxinc.com/intro01.html>

### OTHER TRACE

INFICON HAPSITE Field Portable GC/MS - Test VOCs On-Site

<http://www.hapsite.com/>

Syagen Technology, Inc.: High-Throughput Molecular Analysis

<http://www.syagen.com/>

TDC - Bringing explosives to light - An innovative laser detection system

<http://www.tc.gc.ca/TDC/r&d/v9n1.htm>

### SWISS Institutions

Gruppe Rüstung Internet (Swiss Defence Procurement Agency)

<http://www.gr.admin.ch/>

Bundesamt für Polizei (Swiss Federal Office for Police)

<http://www.admin.ch/bap/>

Institut de Police Scientifique et Criminologie (ipsc)

<http://www.unil.ch/ipsc/>

Le corps des gardes-frontière en bref

[http://www.douane.admin.ch/f/chzollf/kuerze\\_gwkf/gwk\\_kurz\\_f.htm](http://www.douane.admin.ch/f/chzollf/kuerze_gwkf/gwk_kurz_f.htm)

Police Cantonale Genevoise

<http://www.geneve.ch/police/welcome.html>

Wissenschaftlicher Dienst (Scientific Research Service)

[http://www.stadt-zuerich.ch/kap05/stadtpolizei/wissenschaftlicher\\_dienst/index.htm](http://www.stadt-zuerich.ch/kap05/stadtpolizei/wissenschaftlicher_dienst/index.htm)

## 9. Contacts:

The following is a list of institutes, organisations or individuals which have been contacted for the study (per country ordered alphabetically), or which are known or at least strongly supposed to have an interest in the subject. Not all of the contacted persons did necessarily reply. Individual names and coordinates have been omitted; we will try to add them after explicit authorisation and keep the list updated. A number of Websites of interest have in fact already been mentioned in Ch. 8.

### SWITZERLAND

Institut de Police Scientifique et Criminologie (**IPSC**), Univ. de Lausanne (School of Forensic Science and Criminology)

**Police Cantonale Genevoise**, Detachement Specialistes Depiegeage (DSD) (Geneva Cantonal Police)

Service Controle Passagers, **Aeroport de Geneve**, (Passenger Control Service, Geneva Airport)

Paul Scherrer Institut (**PSI**), Villingen

**SM** Altdorf (Swiss Ammunition Enterprise Corp.)

**EPFL-DP-IGA** (Institut de Génie Atomique – Institute of Nuclear Engineering)

**Bundesamt für Polizei** (BAP), Dienst für Analyse und Prävention (Federal Office for Police, Service for Analysis and Prevention)

Stadpolizei Zuerich, Wissenschaftlicher Forschungsdienst (**WFD**) (Zurich City Police, Scientific Research Service)

Commandement (du Corps) des Gardes-Frontiere (**Grenzwachtkorps**), Geneve (Frontier Guards Command, Geneva)

Kantonspolizei Zuerich, **Flughafenpolizei** (Zurich Cantonal Police, Airport Police)

### OTHER

Institut fuer Rechtsmedizin, Univ. Bern (Forensic Medicine Institute)

Geneva International Centre for Humanitarian Demining (GICHD)

Police Cantonale Vaudoise, Groupement Specialistes Depiegeage (Canton of Vaud Police)

### GROUPS / LISTS

analysisexplosives@egroups.com (moderated by J. Yinon – see USA)

### AUSTRALIA

Department of Physics, Univ. of Melbourne

Defence Science and Technology Organisation (DSTO)

University of Western Australia (UWA)

### AUSTRIA

International Atomic Energy Agency (IAEA)

### CANADA

Security Specifications and Guidance Material Section, ICAO Headquarters, Montreal

Laboratory for Threat Material Detection, Department of Mechanical Engineering, University of New Brunswick (UNB)

John McFee, Defence Research Establishment Suffield (DRES)

Canadian Centre for Mine Action Technologies (CCMAT)

New Technology Div., Barringer Research

### CROATIA

Ministry of Interior

Croatian Mine Action Centre (CROMAC) Scientific Council

### DENMARK

DEMEX

CAT

### FRANCE

SODERN

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

TDA Armements SAS  
Ecole Polytechnique  
CEDALES  
EPPRA Sarl  
Commissariat a l'Energie Atomique (CEA-LETI), Grenoble  
Institut de Saint Louis (ISL)  
Thomson-CSF Detexis  
Delegation Generale a l'Armement (DGA), Centre d'Etudes du Bouchet (CEB)

### *GERMANY*

IABG, Munich  
Bruker Saxonian Analytik GmbH, Leipzig  
Fraunhofer Institut fuer Chemische Technologie (ICT)  
Institut fuer Umwelttechnologien (IUT), Berlin  
TZN  
Wehrwissenschaftliches Institut fuer Schutztechnologien (WIS), ABC-Schutz, Munster (German Armed Forces Scientific Institute for Protection Technologies – NBC-Protection)

### *ISRAEL*

SOREQ

### *ITALY*

Univ. Trento  
Joint Research Centre (JRC) Ispra  
LNL / INFN  
ABC  
Univ. Padova / INFN

### *NETHERLANDS*

TNO-FEL  
Dutch Forensics Science Laboratory, Section Explosives  
TU Delft

### *RUSSIA*

Department of Physics, Kaliningrad State University  
Joint Institute for Nuclear Research, Dubna, ?  
Institute of Applied Physics, Novosibirsk  
Department of Applied Nuclear Physics, Cherenkov Laboratory, Lebedev Physical Institute (LPI) of RAS (Russian Academy of Science)

### *SLOVENIA*

IJS (Jozef Stefan Institute)

### *SOUTH AFRICA*

CSIR  
MECHEM  
Department of Physics, University of the Witwatersrand

### *SWEDEN*

Swedish Defence Research Establishment (FOA) Linköping  
Biosensor Applications AB  
Swedish Defence Research Establishment (FOA) Stockholm  
SWEDEC

### *UNITED KINGDOM*

Royal Military College of Science, Cranfield University  
BTG PLC

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

John Caunt Systems  
BARIC Consultants  
DERA Fort Halstead (?), Sevenoaks  
ERA Technology  
Institute of Munition Clearance Engineers  
DERA Porton Down  
BACTEC  
King's College London (KCL)  
Chemical and Biological Weapons Research Unit (Porton Down), DERA  
RV Consultancy

### *UNITES STATES*

Inficon, portable GC/MS  
Ancore Corp (ex Advanced Nucleonics Division of SAIC)  
SAIC (US) (Science Applications International Corporation)  
Poulter Laboratory, SRI International  
Univ. of Florida  
Univ. of Maryland  
Harvard  
Special Technologies Laboratory, Department of Energy (DoE)  
Southwest Research Institute (SwRI)  
James Madison University (JMU)  
HiEnergy Microdevices  
Federal Aviation Administration  
Bombs Away, Guam  
Chemical & Engineering News  
Applied Physics Institute, Western Kentucky University, PELAN system  
National Center for Forensic Science, University of Central Florida

### *ARMY, Defence (General)*

OE Team, U.S. Army Engineering and Support Center (USACE), Huntsville  
Technology Integration, Pentagon  
U.S. Army Engineering and Support Center (USACE), Huntsville  
UXO Center of Excellence (UXOCOE)  
Institute for Defense Analyses (IDA)  
US Army Environmental Center (AEC), Aberdeen Proving Ground  
US DoD SO/LIC (Special Operations/Low Intensity Conflicts)

### *ARGONNE National Labs*

Argonne National Lab (ANL)  
Argonne National Lab (ANL) Technology Transfer

### *INEEL (Idaho National Engineering and Environmental Laboratory)*

INEEL  
UXO/Demining Initiative, INEEL  
Integrated Defense Systems

### *NAVY*

NRL (Naval Research Lab)  
Navy EOD Technology Division (NAVEODTECHDIV)  
Research & Development, Naval Facilities Engineering Service Center, Port Hueneme, CA

### *QM (Quantum Magnetics)*

## Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)

Quantum Magnetics

*SANDIA National Labs*

Contraband Detection Technologies Department, Sandia National Laboratories

Explosive Technologies Group, Sandia National Laboratories

## ANNEX:

### A1. Other Explosive/Contraband Detection Technologies:

#### A1.1. Neutron Backscatter:

**Neutron backscatter** is probably the simplest neutron based technique. It relies on fast neutrons emitted into the target (as we have seen they can penetrate easily several cm of steel if necessary), where they are slowed down by collisions with hydrogen nuclei. The number of detected backscattered thermalised neutrons, i.e. slow neutrons coming back in the direction of the source, provides a measure of the hydrogen content of the material. These devices are therefore also called “Neutron Thermalisation Gauges” (NTG), and are in current use in a number of other fields (ex. petroleum industry).

*Current applications of neutron backscatter systems include for example the discrimination of ordnance containing explosives, inert substances and chemical warfare agents based on the considerable differences in their hydrogen content.* A system has also been reported to have been in use for quite some time to detect explosives hidden in car doors, tyres, etc. For the detection of buried objects (e.g. landmines) the system has problems in presence of too much water and seems therefore likely to only work in dry or slightly humid environments. Tests with a *time-tagged radioactive source* are detailed in [CRA00] (for landmine detection).

The “**Neutrotest**” system developed by I.U.T. (<http://www.iut-berlin.de/>), for example, is composed from a technical point of view of a BF<sub>3</sub> proportional neutron counter and a fast neutron radioactive source, usually of the AmBe (Americium-Beryllium) type, located in the same head<sup>36</sup>. The final system is rather light and simple, and gives a quick answer useful to prescreen objects. *Known calibration curves are used, or scaling factors when encountering new geometries.* In the case of larger munition several measurements might have to be taken along its profile.

**HCM** (Hydrogen Concentration Monitor), developed by the German Armed Forces Scientific Institute for Protection Technologies – NBC-Protection (WIS-ABC) in Munster, Germany, uses a small and weak <sup>252</sup>Cf source and a <sup>3</sup>He thermal neutron detector [BUC98]. The dimensions of the sensor system are 50x60x200 mm with a weight of 1.2 kg. As some background is generated in the floor and the walls of a building, a certain distance from the floor, depending on the object being analysed, is necessary. A counting time of 60 sec is sufficient to accumulate about 1000 events (i.e. backscattered neutrons), which results in a statistical uncertainty of 3%. The counting rate is influenced by the diameter of the samples (shells), the wall thickness and material. **Standard calibration curves** have therefore to be measured for different shell calibres and wall materials, and correction factors for pallets for example. A database containing the detailed calibration curves is integrated into the HCM evaluation software. The HCM is in use by the OPCW (Organisation for the Prohibition of Chemical Weapons) inspectors.

HCM is sold in Germany by ESM Eberline Instruments GmbH, Frauenaauracher Str. 96, D-91056 Erlangen, Germany, Tel. +49 (0)9131-909-0, Fax +49 (0)9131-909-205. It is distributed in other parts of Europe by John Caunt Scientific Limited, PO Box 1052, Oxford OX2 6YE, UK (<http://www.johncaunt.com/>, John Caunt <[johncaunt@dial.pipex.com](mailto:johncaunt@dial.pipex.com)>).

The application of neutron backscatter systems for the task of interest to us is likely to be problematic: 1) for *partially buried munition* (soil influence), 2) for *unknown munition* (unknown calibration curve), 3) and possibly also when detecting *black powder* (does not contain hydrogen, see §1.1) or *incendiary munition* (does usually not contain hydrogen). Hydrogen will be present in some inert fillers such as waxes, or whenever some water is present, which might increase the false alarm rate. On the other hand it might still be true that when no signal is detected no hydrogen – and therefore no explosive – is contained in the UXO. *Whether this turns out to be useful in practice remains to be seen, but the simplicity of neutron backscatter devices might well warrant some practical investigation.* Obviously only if it is possible to put the detector in contact with the UXO, or at least in close proximity.

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<sup>36</sup> The I.U.T. “Neutrotest” documentation specifies that “fast neutrons penetrate easily 4 cm thick steel walls”.

[BUC98] F.-W. Buchholz, L. Schänzler, G. Tumbrägel, “Non-Destructive Evaluation (NDE) of Chemical Weapons: Hydrogen Concentration Measurements (HCM) by Thermal Neutron Detection”, German Armed Forces Institute for Protection Technologies – NBC-Protection (WIS-ABC), Munster, Germany, Nov. 1998.

### A1.2. Gamma Backscatter:

**Gamma backscatter** sensors are relatively simple units that can be employed to *detect hidden organic material, typically drugs or other contraband*, based on the fact that the latter (the lighter elements) generates intense backscattering when hit by the emitted  $\gamma$ -rays. For some information on the current applications of such units and the physics behind them see for example <http://www.bicron.com/notegauging.htm>.

An example of such a sensor is the **SEARCHER** unit, which is already in use for police and customs applications. The unit is battery powered and one-man portable, and relies on a cobalt-57 ( $^{57}\text{Co}$ ) source and associated detector electronics to detect the presence of material within a depth of about 10 cm. A simple audible signal is delivered, which also depends on the thickness of the material being analysed; with use the operator learns to interpret the audible signals. The source has a half-life of 270 days, therefore a source change is recommended every two years (although adjusting the gain allows to reach four years). Note that when the probe is turned ON and in use, no part of any person should be allowed within 30 cm of the face of the probe. The approximate price is in the 10.000£ range.

The SEARCHER was developed by JCS (John Caunt Scientific Limited, coordinates as in §A1.1), and is sold through S&D Security (Equipment) Ltd.

The SAIC CDS-2002i™ *Contraband Detector* is probably another unit working on similar principles. It employs a low-level 100  $\mu\text{Ci}$  (Standard) or a 10 $\mu\text{Ci}$  (Exempt)  $^{133}\text{Ba}$  radioactive source, and is detailed at [http://www.saic.com/products/security/contraband\\_detector/cds.html](http://www.saic.com/products/security/contraband_detector/cds.html).

### A1.3. CWA Chlorine Detection by TNA:

We have already seen that TNA systems are also employed for the detection of typical key elements in Chemical Warfare Agents (CWA). As TNA is very sensitive to **chlorine** (i.e. chlorine can be easily detected), and chlorine is present in a large number of CWA, in particular old chemical weapons<sup>37</sup> such as those from WWI, specific simplified TNA systems have been designed and are available.

One of them is **CDS** (Chlorine Detection System) by the German Armed Forces Scientific Institute for Protection Technologies – NBC-Protection (WIS-ABC) in Munster, Germany, which was presented to the OPCW (Organisation for the Prohibition of Chemical Weapons) in Sept. 1997 partly as an alternative to the more comprehensive but larger NIPPS system (see §3.4). CDS is a small and rugged device relying on a  $^{252}\text{Cf}$  source (10 times less intense than for the normal NIPPS system) and on a compact uncooled BGO detector to detect the chlorine capture  $\gamma$ -rays (the most intense have an energy of 1.165, 1.955 and 6.111 MeV). Chlorine concentrations above 20 g can be measured in 2 to 5 minutes [BUC97].

CDS is sold in Germany by Target Systemelectronic GmbH, Kölner Str. 99, D-42651 Solingen, Germany, Tel. +49 (0)212-2220-9090, Fax +49 (0)212-201045.

[BUC97] F.-W. Buchholz, L. Schänzler, G. Tumbrägel, “Chlorine Detection by a Simple NIPPS System: CDS”, German Armed Forces Institute for Protection Technologies – NBC-Protection (WIS-ABC), Munster, Germany, Sept. 1997.

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<sup>37</sup> All blister agents and all choking agents as well as most irritants contain large portions of chlorine.



### A1.4. Nuclear Magnetic Resonance (NMR):

The **Nuclear Magnetic Resonance (NMR)** technique is based on the ability to measure the characteristic absorption of radio frequency (RF) signals by certain nuclei of a target material. To induce nuclear magnetic resonance, a sample material is placed in a volume surrounded by large magnets that produce a (usually strong) uniform magnetic field. The nuclei of the sample material, subjected to this directional magnetic field, align themselves in the applied field according to their nuclear magnetic moment. As sample atoms are energised by an external source (a weak radiofrequency field, in the MHz range), they will transition between discrete energy states, as dictated by their magnetic alignment, and thus absorb a fraction of the incident radiofrequency (RF) energy. The measurement and chemical interpretation of these energy transitions constitute NMR analysis. The frequencies at which the probe absorbs some RF power (i.e. peaks in the frequency spectrum) are determined in practical terms either by sweeping the frequency itself, or by keeping it fixed and modulating the intensity of the applied magnetic field (see also [YIN99]).

A particular form of NMR, the **Fourier Transform Proton** (i.e. Hydrogen) **NMR (FT-<sup>1</sup>H-NMR)**, has been suggested for the detection of explosives. By analysing and processing the total hydrogen NMR signal, any contribution to the response produced by hydrogen in explosives can be separated from that (usually much larger) produced by the hydrogen in most other materials. In practical terms, the RF field is applied in short pulses of controlled width and amplitude, and the corresponding NMR responses are transient RF signals emitted by the excited nuclei. Two parameters have a particular importance,  $T_1$  and  $T_2$ .  $T_1$  is the so-called spin-lattice relaxation time, which is the characteristic time for a nuclear spin system to come to equilibrium with its surroundings after a disturbance (such as the previously mentioned RF pulses, or a change in the applied field).  $T_1$  sets the time required to detect an NMR response, and the rate at which NMR tests might be repeated without signal degradation.  $T_2$  is the so-called spin-spin relaxation time, which is the characteristic time for a spin system to come to transversal equilibrium following a disturbance. The transient, free induction decay (FID) signal following a single transmitter pulse decreases in amplitude at a rate which is dependent upon  $T_2$  (in a homogenous magnetic field).

*$T_1$  and  $T_2$  are characteristic of the molecular structure and the state of the sample material.* Measurements have been reported, in particular at a frequency of 3 MHz, showing that *these two constants for explosives can be well separated from other common materials of interest*,  $T_1$  being long (1-10 sec) and  $T_2$  short ( $10^{-4}$ - $10^{-6}$  sec). Additional selectivity is provided in FT-<sup>1</sup>H-NMR by the <sup>1</sup>H-NMR to <sup>14</sup>N-NQR level crossings, but we will not go here into further details. Note that the sensitivity is not affected by the distribution of the sample, only by the total material present.

NMR techniques can therefore determine the presence of materials with the chemical composition of explosives. The FT-<sup>1</sup>H-NMR technique described above has been in particular extensively tested. All samples, however, must be passed through the magnetic coils (with a higher field intensity allowing higher signal to noise ratios), thus limiting accessibility and configuration of NMR systems. This is probably one of the reasons why no such systems are commercially available, to the best of our knowledge. Other reasons might be the detection time, or the need for very good field homogeneity over large working volumes. The inability of detecting explosive contained within metallic enclosures (screening by Faraday effect) might also be a problem (see also the NQR section). Iron or large amounts of ferromagnetic metals can cause field distortion and reduce effectiveness.

NMR techniques for the detection of explosives have been for example extensively studied at the South West Research Institute (<http://www.swri.org/>). See for example “Baggage Inspection Apparatus and Method for Determining Presences of Explosives”, A. De Los Santos, J. D. King, W. L. Rollwitz, G. A. Matzkanin, P. A. Hornung, South West Research Institute, US Patent # 4,514,691, 30/04/1985, and also [YIN93a]. NMR techniques for drug detection have also been studied at Quantum Magnetics (<http://www.qm.com/>).

We will not enter here into the details of another RF resonance absorption method, *Electron Spin Resonance (ESR)* or *Electron Paramagnetic Resonance (EPR)*, just mentioning that it is limited to small proportion of materials (those which have free spins), but when applicable is much more sensitive than NMR. One such material is *black powder*, which cannot be detected by proton NMR (it does not contain hydrogen).

### A1.5. Nuclear Quadrupole Resonance (NQR):

**Nuclear Quadrupole Resonance (NQR)**, a derivative of NMR, is a bulk inspection technology for detecting crystalline explosive solids containing *nitrogen-14* ( $^{14}\text{N}$ ) nuclei such as RDX, TNT, and nitrates. NQR has been described as “an electromagnetic resonance screening technique with the specificity of chemical spectroscopy”.

Unlike NMR where an external (static) magnetic field is needed, quadrupole resonance takes advantage of the material's natural crystalline electric field gradient<sup>38</sup>, i.e. the electrical gradients available within the molecule itself. These gradients are due to the distribution of the electrical charge within the molecule and *do therefore depend on the chemical structure* (they will be different for RDX, for TNT, etc.). The electrical field gradients align the electric quadrupole moments, which are a physical property due to a non-spherical (say ellipsoidal) nuclear charge distribution, of the  $^{14}\text{N}$  nuclei. As a result, the material being diagnosed need not be contained within large magnetic field-producing coils. NQR resembles therefore to NMR without a magnet.

When a low-intensity RF signal is applied to the material at certain frequencies, usually in the range 0.5 to 6 MHz, the alignment of the  $^{14}\text{N}$  nuclei is altered. As the RF is removed, the nuclei precess to their original state (actually a transition between the energy states resulting from the previously described interaction), producing a characteristic radio signal. The signal can then be measured for analysis. Detecting the presence of explosives becomes similar to tuning a radio to a particular station, and the uniqueness of a molecule's electric field allows NQR technology to be highly compound specific. This high selectivity is partly a disadvantage, as it is apparently not that easy to build a multichannel system necessary to cover a wide range of target substances.

The actual setup (geometry) depends on the application at hand, and there are a number of situations, such as in landmine detection and perhaps for the identification of IEDs, in which a *single-sided (remote) geometry is necessary*, as it might be impossible to put parts of the sensor on “the other side of the object”. Also, similarly to metal detectors the generated and the received field decay very quickly with distance; the detection distance will therefore be limited and the equipment will probably have to be used in close proximity to the object or to the ground. Power requirements are also considerable. Whether these issues are problematic depends obviously a lot from the target application.

*The impossibility of detecting substances fully screened by metallic enclosures* (also foils, depending on their thickness) is an issue like for NMR. What will however probably happen is that the presence of such objects throws the NQR probe out of tune, in which case the operator knows that something is wrong. It might also still be possible to detect explosives in imperfectly shielded objects, e.g. within metallic containers having holes or slots or other regions where there are poor electrical connections (possibly even some UXO!)<sup>39</sup>, but this will result in a correspondingly weaker NQR signal. Practical applicability is therefore likely to be an issue.

Detection times are likely to be higher than a few (tens of) seconds, depending on type and quantity of the target substance (especially on its  $T_1$  relaxation time), and on its distance for one-sided applications. In addition, the signal to noise ratio increases with frequency as  $\omega^{3/2}$ , which implies that *detection of TNT is much harder than detection of RDX*, for which NQR systems have been shown to be very promising<sup>40</sup>. Signals are in general rather weak, so that some form of signal averaging is usually necessary – as well as shielding, because the detector will work (at least for TNT) straight in the AM broadcasting band! Spurious signals have also been reported due to “*acoustic ringing*” effects (due to certain metals and metal coatings), as well as due to *piezoelectric responses* from silica in the soil (for applications such as landmine detection). All these effects are being tackled using appropriate pulsing sequences and detection software, as well as

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<sup>38</sup> A field's gradient corresponds to its spatial derivative, and is therefore only different from zero when the field is not homogeneous.

<sup>39</sup> John Smith, King's College London, *Private Comm.*, June/July 2000.

<sup>40</sup> The spectral lines of TNT are all below 1 MHz, those of RDX are at 3.410 MHz and 5.192 MHz (amongst others).

specific hardware. Care will have also to be taken of the temperature dependency of the spectral lines, selecting for example those NQR transitions which are least affected by temperature changes (e.g. 3.410 MHz line instead of 5.192 MHz for RDX).

NQR for explosive detection has been intensively researched in both the UK and US in the context of defence applications, in particular in the UK at King's College in London (KCL, Prof. John Smith) under sponsorship of DERA, at DERA itself and at ERA Technology (especially equipment manufacturing, <http://www.era.co.uk/>, David.Daniels@era.co.uk) [BRU99]. In the US Quantum Magnetics, now part of InVision Technologies, has licensed the NQR technique from the Naval Research Lab and is also currently engaged in prototype developments (<http://www.qm.com/>). At the time of writing there are actually two systems being advertised by Quantum Magnetics, the QSAN™ QR160 (for carry-on baggage) and the QSAN™ QR 500 (for checked baggage, mail and parcels); these detectors are two channel systems. Some prices are quoted in [NIJ98]. R&D was also carried out in the former Soviet Union, in Kaliningrad (Prof. Grechiskin, Kaliningrad State University) and in Novosibirsk, as well as in Slovenia (R. Blinc, Jozef Stefan Institute, Ljubljana). Note that some of the work has also been aimed at the analysis of suspicious objects using different system configurations, but no commercially available systems have appeared yet (equipment is only available to a bespoke design requirement).

## A2. Operational Aspects:

In order to better carry out this study we tried to analyse the task at hand also from an **operational point of view** (i.e. if and how explosive detectors are used in practice, or could be used), in addition to working on the technical point of view (sensor analysis). To better cover the spectrum of explosive detection several interviews were carried out mainly in Switzerland with representatives of the Police forces, EOD teams, the Police Scientific Research Service, and airport security.

A few key points will be summarised in the following paragraphs, which do not pretend to be exhaustive, also because *individual techniques often vary considerably according to the precise circumstances and much can be left to individual judgement*. In addition, the case of Improvised Explosive Devices (IEDs) presents understandable security issues.

Operational aspects and scenarios pertaining to Law Enforcement applications are considered in detail in [NIJ99a, NIJ98], as well as in [NAV97].

### A2.1. Explosive Ordnance Disposal (EOD) Tasks:

We are considering here mainly **Explosive Ordnance Disposal (EOD)** tasks as carried out routinely and domestically. *In most cases the UXO should not be touched nor displaced, at least initially. The main problem is to establish if the UXO is inert or not* (and in some cases if it is incendiary, containing phosphorus, or not). A judgement is formulated using several elements which help in identifying the munition:

- Presence of **coloured bands** arranged according to a precise colour code (with some exceptions as usual...).
- **Comparison** with printed handbooks or electronic databases.
- General information on the munition's **history** (if available), how it was found, where it was found, etc.
- Other **background knowledge**, e.g. which munition is predominant in a given area (most common main explosives: TNT, RDX). Chemical munition is an issue in a number of areas of Belgium, France and Germany for example.
- **Technical means** can be employed to determine the **munition's state and internals** (often of the **detonator**), typically **X-ray systems** combined with *radiographic films* or *real-time imaging systems* (zoom possibility, image enhancement, image storage capability, possibility of sharing images), or  $\gamma$ -ray based devices (e.g. Gammamat). For the latter security concerns have been raised by some operators due to the need for a possibly intense radioactive source. X-ray images are for example used in some scenarios to determine if the munition contains chemical warfare material by slightly inclining it (a diagonal line corresponding to the liquid level can be seen), or if it contains a detonator different from the one of the standard munition.

When the object has been identified it can be rendered safe according to known procedures, to be then disposed of later on, or destroyed in situ if necessary and possible. If the UXO cannot be identified, for example when the object is in a very bad state or when it is unknown, a decision has to be taken based on the elements at hand. Normally one tends to minimise risks and stay on the safe side. Possible destruction means include standard (TNT) explosives charges, shaped charges (e.g. from the Swiss Ammunition Enterprise Corp., or SM), or pyrotechnic torches where applicable (FireAnt, etc.).

Still concerning X-ray systems, INEEL (Idaho National Engineering and Environmental Laboratory) has developed a field portable X-ray Digital Radiography and Computed Tomography (DRCT) scanner, which has allowed to obtain high-quality radiographs and tomographic<sup>41</sup> images of (chemical) munition at the site where the munition is stored or recovered [RON00]. Stereoscopic methods have also been suggested to provide information about the depth structure of the object being analysed [RAN99]. Fixed site tomographic

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<sup>41</sup> A 3D volume of information is acquired and processed; it can then be displayed as 2D images along any axis.

installations for Non-Destructive Ordnance Evaluation have also been reported, but these are probably large systems and do not directly concern EOD applications.

Last but absolutely not least, whether or not the probing method or system being investigated risks to activate the UXO's detonator, either because of the probing radiation itself or because of the system's electronics for example, should obviously be known or checked beforehand (!).

## A2.2. Improvised Explosive Devices (IEDs):

As we already said, the case of **Improvised Explosive Devices (IEDs)**, which is mostly a *Police task*, presents understandable security issues, particularly concerning the details of the actual operational procedures. This fact, combined with this study's priority being on the UXO rather than on the IED side, results in the following information being far from exhaustive. Some aspects related to *Airport Security* are dealt with later on.

To analyse the object's state and internals *portable X-ray equipment* is used by some units, again combined with radiographic films or real-time imaging systems (most of the comments of A2.1 still apply).

Concerning bulk explosive detection, *neutron backscatter* devices, which are basically hydrogen detectors, have apparently also been employed (see A1.1). Thermal Neutron Analysis (TNA) systems have been tested for airport security applications (see also A2.3). They seem to be commercially available in different versions, e.g. from the ANCORE Corp., to check mail, parcels, cars, etc., mostly as fixed installations. Their actual level of diffusion is not clear. Whether neutron based systems will get really portable remains to be seen. *Radiation hazard* is obviously also present and has to be dealt with. For a description of advanced X-ray systems see again §2.1, and §A2.3.

Work is ongoing on *Nuclear Quadrupole Resonance (NQR)* based systems (see A1.5), for example either by using a single coil in a one sided geometry, or by employing pairs of coils when the object can be accessed from both sides. *Nuclear Magnetic Resonance (NMR)*, (see A1.4) was also seen as a potential candidate in the late 80's, early 90's.

Trace explosive detection devices are on the other hand widely available, although opinions diverge on their practical applicability for this task. One of the key issues resides in how to bring the explosive (in)to the probe and how to maximise the sampling efficiency, see for example §4.1 and Annex A3 as well as the references cited therein.

### A2.3. Airport Security:

Detection of explosive devices is obviously also an issue in **airport security applications**, and a particularly challenging one. The only **bulk explosive detection** systems in widespread use seem to be *advanced X-ray machines* (see §2.1), incorporating a range of innovations such as backscatter, dual energy X-ray beams, tomography for 3D object analysis, and possibly X-ray diffraction pattern analysis. They can provide automatic threat detection algorithms or at least assist the operator in taking a decision. In either case, at the end of the day it is necessary to appropriately balance detection rate with false alarm rate [YIN99]. Standard X-ray machines have obviously been used for quite a long time, but as we said more in the role of systems to detect weapons and the clues to the explosive device such as switches, detonators, wires, etc., rather than the explosive itself.

New bulk explosive detection techniques seem to have been tested in the last years, for example NQR or TNA, but apparently it is not easy to satisfy all the requirements, in particular the need for high throughput (and therefore little time for each piece of luggage, say some seconds) coupled to a reasonably low false alarm rate. A reasonable cost and complexity do also play a role, as well as environmental factors for example in the case of neutron based systems. An additional complexity comes from the need of having to detect a relatively small device in a large complex and variable matrix (a piece of luggage and its contents). As an example, problems with TNA systems due to the presence of other nitrogen containing substances (including food!) have been reported. On the other hand, the dissuasive role of explosive detection equipment should probably not be underestimated.

**Trace explosive detection has seen an increasing level of success in the last couple of decades**, is now routinely featured in a number of airports and seems to feature a rather low false alarm rate. Particle detection in particular is feasible, as the objects at hand can be touched and swiped. To have an idea of which trace explosive detection systems are deployed see for example [NAP99, Ch. 7] for the case of US airports.

### A2.4. Search Applications:

Search applications involve situations where a bomb is suspected of being in a general area, but the exact location is unknown. This would include, for example, searching a building or property grounds for a bomb, once a bomb threat has been communicated. In most search applications, canine detection will be the detection method of choice because of the dog's rapid mobility and its ability to follow the scent to its source.

We will not enter here into further details, nor cover other applications such as the detection of explosives in large containers.

### A3. Commercially Available TRACE Explosive Detection Systems:

The following subsections discuss specific **trace explosive detection** technologies. As **reference documents** we have based ourselves on [YIN99] and in particular on the [NIJ99a] **market survey** of trace and X-ray based commercial detection systems for Law Enforcement applications (known to the authors as of October 1998), from which we quote extensively without necessarily repeating in each paragraph the reference to these two publications. A listing of different trace technologies and their acronyms has already been given in Table 5. [STE98] also contains a wide overview and a large number of references.

As in [NIJ99a], inclusion of specific technologies in this document does not represent endorsement of the corresponding systems. Also, these references do not pretend to be all-inclusive.

#### A3.1. Ion Mobility Spectrometry (IMS):

**Ion Mobility Spectrometry (IMS)** makes use of the different mobilities<sup>42</sup> of ionised species in gases and is one of the most widely used techniques for trace detection. The spectrometer consists of two main sections: the *ionisation region* and the *drift region*. Ambient air is typically drawn into an inlet port at the rate of a few hundred cubic centimetres per minute (ccm/min) and enters the ionisation region, where electrons interact with the incoming molecules to form positive or negative ions (as in the case of explosives). The source of the ionising electrons is a small, sealed piece of metal that has been coated with a radioactive material, usually nickel-63 (<sup>63</sup>Ni). Tritium has also been used (e.g. in the I.U.T. IMS system).

The ions are then periodically admitted into the drift region through an electronically shuttered gate. This “drift” of the ions from one end of the drift region to the other occurs at *atmospheric pressure*, with many collisions between the ions and the various molecules present. The time it takes the ions to travel the length of the drift region is called the *drift time* and depends on their mobility. The drift time is a complex function of the charge, mass, and size of the ion (and its molecular structure?), and allows the identification of the substance. Typical drift times are on the order of a few milliseconds (1 ms = 0.001 s). Examples of ion mobility spectra are shown in [YIN99] as well as in several of the manufacturers’ brochures.

The current collected at the metal plate is measured as a function of time, and *an IMS spectrum is a plot of ion current versus time*, with different peaks representing different specific ions. Sometimes an additional gas called the dopant or carrier gas is admitted into the IMS to aid in the ionisation process; very commonly methylene chloride or some other gas that easily forms chloride ions is used. Ions from this gas usually form the largest peak in the IMS spectrum, commonly known as the reactant ion peak or RIP, which serves as a reference peak. The overall signal to noise ratio is usually increased by repetitively scanning the spectrum and signal averaging (a single mobility spectrum can be generated in some tens of msec).

A number of companies market IMS systems, see Table 6. Upkeep costs vary from system to system, but are moderate in most cases. Most IMS systems are small and portable enough to be moved around in a standard vehicle, and can be operated by a person with only a few hours of training. These instruments have response times of only a few seconds, the proven ability to detect a number of key explosives, sub-ppb/sub-nanogram<sup>43</sup> sensitivity and low false alarm rate. The most effective means for collecting a sample for presentation to one of these systems is surface swiping, but vacuum collection of samples is also possible with many systems. Some of the potential drawbacks include:

- The presence of a small sealed radioactive source, more on the licensing side (the source does not pose any health risks).
- IMS is carried out at atmospheric pressure. Recalibration may be necessary when the atmospheric pressure changes (e.g. when changing altitude by more than 100 m say, or during inclement weather, e.g. storms), as the drift time is affected and therefore the peak positions.
- The warm-up time is usually of the order of 10 min, but up to 1 hour has also been reported.

<sup>42</sup> An ion’s mobility is defined as the ratio of drift velocity and applied electric field.

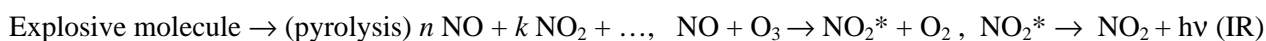
<sup>43</sup> Tens to hundreds of picograms, see also Table 6 and [YIN99].

- The ion mobility spectra can be quite complex! But it is true that the end user does not necessarily have to look at them.
- Decontamination time (after an excess of substance) can be an issue, possibly up to several hours.
- Peak resolution might not be sufficient for certain applications (two different ions of similar size and mass may appear to give only a single peak rather than two distinct peaks). This might happen for example in the presence of several kinds of compounds in the probe sample, resulting in increased complexity of the ion mobility spectra, which often cannot be interpreted exactly.

The last problem can be eased by adding a **Gas Chromatograph (GC)** to the IMS, which is basically a hollow tube, usually packed with beads that are coated with a special chemical substance, referred to as the stationary phase. This coating interacts more strongly with some molecules than with others, so if a gas flow containing different types of molecules is admitted into the GC, molecules that interact more strongly with the stationary phase will take longer to pass through the column. *This means that an originally random mixture of different molecules can be sorted by type, with each species exiting the GC at a different time (the retention time).* And if two molecules have identical drift times in an IMS, they will almost certainly have different retention times in the GC, and their peaks can thus be temporally resolved because they will enter the IMS at different times. Combined systems of this type are referred to as **GC/IMS** and are obviously somewhat more expensive, featuring longer analysis times as well.

### A3.2. Chemiluminescence (CL):

Most explosive compounds contain either nitro (NO<sub>2</sub>) or nitrate (NO<sub>3</sub>) groups (see also Table 1), a fact which is exploited by detectors based on the **Chemiluminescence (CL)** principle (CL devices are also known as **Thermal Energy Analysers**, or **TEA** [YIN99]). In these detectors explosive molecules are first pyrolyzed to produce nitric oxide (NO), which then reacts with ozone (O<sub>3</sub>) in an evacuated reaction chamber maintained at a pressure of about 3 torr (0.4 kPa), resulting in excited state molecules, NO<sub>2</sub>\*. The latter de-excite to NO<sub>2</sub> by emitting infrared light of a characteristic frequency (0.6-2.8 μm), which is detected by a photomultiplier placed behind a red filter to block any light with frequency higher than the near IR. The photomultiplier's signal output is directly proportional to the amount of NO present in the reaction chamber. Summarising (*n, k* depend on the explosive type and the reaction conditions):



Chemiluminescence by itself is not capable of identifying what type of explosive molecule is present, as the NO could have been produced by other substances (i.e. interferences). CL detectors are therefore coupled to a front-end gas chromatograph (GC), which allows different molecules that are detected with the chemiluminescence detector to be specifically identified based on their GC retention times. An example of such a GC/CL detector is the Thermedics EGIS, which is capable of analysing samples in 18 seconds. Because of its high sensitivity and excellent selectivity it is a popular system with laboratory researchers and forensic analysts [NIJ99a] (although 2 to 3 times more expensive than typical IMS systems).

### A3.3. Electron Capture Detectors (ECD):

An **Electron Capture Detector (ECD)** detects explosives and other types of molecules having high electron affinities (ECD is therefore not compound specific). A vapour sample enters the detector and mixes with a stream of inert carrier gas, usually helium or argon. The gas flow travels then through an ionisation region, passing through a chamber containing a radioactive material, usually either nickel-63 (<sup>63</sup>Ni) or tritium, that acts as an electron source as in an IMS. The emitted electrons become thermalised through collisions with the gas in the chamber, and eventually are collected at an anode. Under equilibrium conditions there is thus a constant standing current at the anode.

The basic principle behind an ECD is that this standing current is characteristic of the gas mixture being drawn into the system. Actually, it is reduced if the vapour of an explosive enters the chamber because the explosive molecules have a high electron affinity and thus a tendency to capture free electrons and form stable negative ions, leaving fewer electrons to reach the anode. As with a chemiluminescence detector, a gas chromatograph is placed on the front end of an ECD system to allow temporal identification of different explosives. For additional information see also [NAV97].



GC/ECD detectors have a rapid response and typical sensitivities of about 1 ppb for most electron-capturing compounds (somewhat less than a typical IMS or CL system<sup>44</sup>, but is still adequate for some applications). At this point we would in fact have to differentiate better between laboratory and field based instruments.

GC/ECD (field?) detectors tend to cost less than IMS or CL, and to be smaller, lighter, and more easily portable. Some of the drawbacks include:

- The presence of a small radioactive source, more on the licensing side (see also IMS comments).
- The need for an ultrapure carrier gas, usually contained in a small cylinder; the availability of this carrier gas can put limits on field applications.
- Lack of specificity and the resulting high rate of false alarms [NAP98b].

### A3.4. Surface Acoustic Wave (SAW) Sensors:

**Surface Acoustic Wave (SAW)** sensors, which are also usually coupled with a front end GC, are based on the properties of a piezoelectric crystal that resonates at a specific frequency. When molecules condense on its surface, the resonant frequency shifts in proportion to the mass of material condensed. The frequency shift also depends upon the properties of the material being deposited, the surface temperature, and the chemical nature of the crystal surface. The SAW surface is maintained at sufficiently low temperatures by a thermoelectric cooler to ensure efficient trapping of the molecules of interest, but can also be heated in order to desorb vapours and thus clean the surface. The temperature of the surface does actually allow control of sensor specificity, by preventing adsorption of species with vapour pressures above a certain level. This feature is useful in distinguishing between high and low vapour pressure explosives. During sampling, vapours are concentrated in a cryo-trap before being desorbed into the GC for temporal separation.

SAW sensors are for example marketed by Electronic Sensor Technology, Inc.. Total analysis time, including sample concentration in the cryo-trap, is typically 10 s to 15 s. The system is advertised to have ppb sensitivity to certain types of explosives, is about the size of a large briefcase, and is operational within 10 min of startup [NIJ99a]. [NIJ98, p. 13] and [YIN99] quote a sensitivity to picogram levels of explosives.

### A3.5. Thermo-Redox (TR) Detectors:

**Thermo-Redox (TR)** technology is based on the thermal decomposition of explosive molecules and the subsequent reduction of NO<sub>2</sub> groups. In practice air containing the explosive sample is drawn into a system inlet at a rate of approximately 1.5 L/min, and then passes through a concentrator tube which selectively adsorbs explosive vapour using a proprietary coating on the tube's coils. The sample is then pyrolyzed to liberate NO<sub>2</sub> molecules, and these molecules are detected using proprietary technology.

The TR system currently marketed by Intelligent Detection Systems (formerly Scintrex), the EVD-3000, is a hand-held unit which can analyse both vapour and particle samples. Since only the presence of NO<sub>2</sub> groups is detected, this technology cannot distinguish among different explosives and potential interferents that contain NO<sub>2</sub> groups.

### A3.6. Field Ion Spectrometry (FIS):

**Field Ion Spectrometry (FIS)** is a relatively new trace detection technology (1994) that is related to IMS. It incorporates a unique ion filter using dual transverse fields, which allows interferences to be eliminated electronically, without the use of GC columns, membranes, or other physical separation methods. FIS is similar to IMS in that it involves separating and quantifying ions while they are carried in a gas at atmospheric pressure; also, a small radioactive source is used for ionisation.

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<sup>44</sup> According to [YIN99, p.35] TEA detectors (i.e. CL) are in fact less sensitive than the ECD by one to two orders of magnitude, although being much more specific for explosives. [NAV9x] quotes a sensitivity limit of 0.01 ng (= 10 pg) of RDX for a lab-based Hewlett-Packard GC/ECD device.

The sole manufacturer of FIS sensors seems to be Mine Safety Applications (MSA). The sensor has no moving parts except for a small recirculation fan and no consumables except for a replaceable calibrator and gas purification filters. The manufacturer has reported detection limits for some high explosives in the low picogram range, as well as a response time of 2 s for a single target molecule plus another 5 s for each additional target molecule (the device can be tuned so that only specific ions, those of interest, can pass completely through the analytical volume and into the collection area for detection).

Because of the newness of this technique, the current systems may be better adapted to laboratory research than to routine field applications, but this could change in the future. The system's maturity is not clear from the corresponding Website.

### A3.7. Mass Spectrometry (MS):

**Mass Spectrometry (MS)** has long been one of the most powerful techniques available for laboratory chemical analysis but is rarely used in routine field applications, also due to system cost, complexity, and the demands of a high-vacuum system [NAP98b]. MS is basically a magnetic filtering technique: molecules are first ionised and then passed through a magnetic filter, which allows ions to be identified based on their charge-to-mass ratio (more details in [YIN99]). In some systems, the MS is connected to a front-end GC.

Mass spectrometers have excellent specificity for identifying different ions, and some (field?) systems have sub-picogram sensitivity. SCIEX (Toronto, Canada) used for example to build a tandem mass spectrometer coupled to an ionisation source operating at atmospheric pressure (API-MS/MS) which was very sensitive<sup>45</sup> (vapour: a few ppt; particle: picogram amount) and fast. Even lower sensitivities are achievable, e.g. 10 fg TNT for a API-TOF MS<sup>46</sup> system quoted in [YIN99, §2.5.2.3]. Sygen (<http://www.sygen.com/>) has developed a QitTof™ (quadrupole ion trap, time-of-flight) mass analyser that is apparently also quite sensitive.

Several portable systems have been advertised in the last years according to [NIJ98], but not necessarily designed specifically for explosive detection. An example is the Inficon HAPSITE field portable GC/MS (<http://www.hapsite.com/>) (weight: 16 kg, batteries included), designed for on-site analysis of volatile organic hazardous air pollutants (VOHAPs) in air, soil and water, for emergency response and environmental applications.

### A3.8. Overview:

Table 6 summarises some information on commercially available trace explosives detection systems as listed in [NIJ99a]. Systems not appearing anymore on the manufacturer's Websites have been omitted (Barringer IONSCAN 350, Graseby PLASTECH, Scintrex/EDS EVD-8000). Most of the portals have also not been included. Needless to say, all information is subject to change. The original cost figures have been retained; they are to be considered as approximate (and probably in general a lower limit), depending on the exact options and accessories as well as on the exchange rate. The original Table has been integrated with information, indicated by the "\*" symbol, from the manufacturers' brochures as well as the [NAV00] Catalogue.

The **USE** is coded as follows: PER/PCK/VEH: Personnel, Package and Vehicle search; PORTAL: Personnel portal (fixed checkpoint portal); POR/LAB: Portable analytical laboratory instrument; NARC/EXPL: simultaneous narcotics and explosives. **Detector Type:** **Vap** stands for vapour detector, **Part** for Particle detector. **Advertised Sensitivity/Detection Time:** **A** stands for *Analysis* time, **S** for *Sampling* time.

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<sup>45</sup> J. McFee, DRES, Canada, *Private Comm.*, July 2000. See also [YIN99, §2.5.2.1], and: W. R. Stott, W. R. Davidson, R. Sleeman, High-specificity chemical detection of explosives by tandem mass spectrometry, Proc. SPIE Vol. 1824, Applications of Signal and Image Processing in Explosives Detection Systems, pp. 68-78, 1992. The system was apparently marketed by BAe/SCIEX as the CONDOR Contraband System.

<sup>46</sup> Atmospheric Pressure Ionization Time-Of-Flight Mass Spectrometer.

**Commercial Systems for the Direct Detection of Explosives (for Explosive Ordnance Disposal Tasks)**

Trace Detector	Cost in k\$	Detector Type	Advertised Sensitivity/ Detection Time	Use	Size / Weight
EXPRAY Field Test Kit <b>Model M1553</b>	0.25	<b>Colour</b>	20 ng of most nitrated high explosives	PER/PCK/VEH	3 aerosol cans, 1 lb.
Ion Track Instruments <b>Exfinder 152</b>	5	<b>GC/ECD Vap</b>	Most nitrated high Explosives A: 1 sec*	PER/PCK/VEH	2"x2"x16" 1.5 lb.
JGW International, Ltd. <b>Graseby GVD4</b>	5	<b>GC/ECD Vap</b>	Explosive vapour Exceeding 1 part in 10 <sup>9</sup>	PER/PCK/VEH	2"x3"x13" 1.6 lb.
XID Corporation <b>XID Model T-54</b>	13	<b>GC/ECD</b>	0.01 ppb	PER/PCK/VEH	4"x12"x17" 18 lb.
JGW International, Ltd. <b>Graseby GVD6</b>	16	<b>IMS Vap</b>	Explosive vapour exceeding 1 part in 10 <sup>9</sup> (1 part in 10 <sup>10</sup> by volume*)	PER/PCK/VEH	22"x4"x13" 21 lb.
Ion Track Instruments <b>Model 97</b>	20	<b>GC/ECD Vap (+Part.)</b>	Most nitrated high Explosives A: 3 sec*	PER/PCK/VEH	14"x19"x6" 40 lb.
Scintrex/IDS <b>EVD-3000</b>	23	<b>TR Vap+Part</b>	< 1 ppb (< 50 ppt for EGDN?) < 100 nanogram for Part. A: 10 sec, S: 5-30 sec	PER/PCK/VEH	4"x5"x20" 7 lb.
Electronic Sensor Tech., Inc. <b>EST Model 4100</b>	25	<b>GC/SAW Vap?</b>	100 ppb? (low ppb*) A(Total): 10-15 sec	PER/PCK/VEH	10"x20"x14" 35 lb.
MSA Instrument Division <b>FIS</b>	29	<b>FIS</b>	10 to 1000 ppt	PER/PCK/VEH	24"x15"x13" 20 lb.
Ion Track Instruments <b>ITMS Vapour Tracer</b>	38	<b>IMS (ITMS) Vap</b>	100 to 300 pg (10 to 50 pg*) A+S(?): 4-10 sec*	PER/PCK/VEH	13"x5"x5" 7 lb.
Ion Track Instruments <b>ITEMISER</b>	44	<b>IMS (ITMS) Part?</b>	100 to 300 pg (<30 pg*) A: 3-8 sec	PER/PCK/VEH	18"x21"x14" 43 lb.
Ion Track Instruments <b>Model 85 Entry Scan</b>	52	<b>GC/ECD</b>	1 part EGDN vapour in 10 <sup>11</sup> parts air	PORTAL	80"x33"x60" 600 lb.
Ion Track Instruments <b>Model 85 Dual Scan</b>	52	<b>GC/ECD</b>	1 part EGDN vapour in 10 <sup>11</sup> parts air	PORTAL	80"x33"x60" 600 lb.
Barringer Instruments, Inc. <b>IONSCAN 400</b>	60	<b>IMS Part</b>	50-200 pg A: 5-8 sec	PER/PCK/VEH	22"x13"x12" 60 lb.
Intelligent Detection Systems <b>ORION</b>	70	<b>GC/IMS Vap+Part?</b>	pg to ng for particulates ppt for vapours. A: 6 sec	PER/PCK/VEH	40"x20"x30" 240 lb.
VIKING Instruments, Inc. <b>Spectra Trak</b>	70	<b>GC/MS</b>	Low ppb By volume	POR/LAB	24"x16"x21" 150 lb.
Intelligent Detection Systems <b>ORION Mail Scanner</b>	75	<b>GC/IMS</b>	pg to ng	MAIL screening	40"x20"x30" 240 lb.
Intelligent Detection Systems <b>SIRIUS</b>	75	<b>GC/IMS</b>	pg to ng	NARC/EXPL	40"x20"x30" 240 lb.
Thermedics Detection, Inc. <b>EGIS Model 3000</b>	150	<b>GC/CL Vap+Part</b>	All nitrogen based Explosives plus taggants A: 18 sec, S:? (10-20 sec?)	PER/PCK/VEH	51"x25"x26" 400 lb.
Intelligent Detection Systems <b>ORION Plus</b>	155	<b>GC/IMS</b>	pg to ng	PER/PCK/VEH	40"x20"x30" 240 lb.

**Table 6: Commercially available Trace explosives detection systems (adapted from [NIJ99a], Table 4; \*: info from the manufacturers' brochures and/or [NAV00]; 1 lb=1 pound=0.454 kg, 1"=1 inch=2.54 cm)**

The following systems represent an addition to those listed in the original [NIJ99a] table, most of them having been marketed since:

- **Barringer Instruments, Inc.:**

IONSCAN 400B: IMS, weight 26 kg, dim. 40x34x32 cm. “Compact” version of IONSCAN 400.

GC-IONSCAN: GC-IMS, “fully transportable field screening instrument” (manufacturer’s notice), weight 32 kg, dim. 41x53x45 cm, analysis time < 5 min (one minute example shown for explosives).

SABRE 2000: IMS, weight 2.6 kg, dim. 33x11.5x13cm, detection limit for most substances: low ng range. Vap+Part, A: 10-15 sec.

- **SIBEL-TDA:**

MO-2M/DOG100: Portable explosives vapour detector MO-2M based on *Non-Linear Dependence of Ion Mobility on electric field (NLDM)*. Joint SIBEL-TDA Russian-French collaboration (SIBEL Ltd., Novosibirsk, Russia; TDA: Thomson-CSF/DaimlerChrysler Aerospace Joint Venture, which markets the detector as DOG100).

Sensitivity: 0.01 ppb for TNT ( $10^{-13} \text{ g/cm}^3 = 0.1 \text{ pg/cm}^3$ )<sup>47</sup>, weight 1.3 kg (hand held unit), dim. 9x10x31 cm, A+S: 2 sec [RAN99]. Marketed as EXPLORER 2000 in the US.

- **I.U.T. (Institut für Umwelttechnologien):**

IMS, weight 6 kg, Vap (+Part), A+S: few secs, GC version available. Price from 30 kDEM, battery powered, also versions for monitoring of chemical warfare agents and narcotics.

- **Thermedics Detection, Inc.:**

EGIS II (possible successor to EGIS model 3000?): GC-CL, sensitivity quoted at 300 pg in [NAV00].

- **Nomadics:**

FIDO system *prototype* aimed at *landmine detection* (see <http://www.nomadics.com/>), based on an extremely sensitive fluorescent polymer. Sensitivity to TNT in the low femtogram range was achieved (say around 10 fg, 1 fg =  $10^{-15} \text{ g}$ ), equivalent to a concentration, based on their sampling approach, of 0.1 ppt (or  $1 \text{ fg/cm}^3 = 10^{-15} \text{ g/cm}^3$ )<sup>48</sup>.

### A3.9. Evaluation of Equipment (for Law Enforcement Applications):

It is worth mentioning that the [NIJ99a] authors have evaluated (see Ch. 4) the previously mentioned systems, trying to define “ideal” and “nominal” characteristics to then classify each detector (when possible). This enumeration is intended only to provide information, whereby the corresponding matrix can serve as an additional starting point in making a procurement decision. This evaluation is **specific to Law Enforcement applications**.

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<sup>47</sup> [RAN99] does in fact quote a sensitivity of better than  $10^{-15} \text{ g/cm}^3$  or 0.1 ppt, with a S/N ratio 5-6, for a “MO-3” detector (?!).

<sup>48</sup> An even lower value of 0.01 ppt = 10 ppq (parts per quadrillion) is quoted on the Nomadics Website as of Sept. 2000.