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Review / Praca przeglądowa

Explosives field detectors – state of the art and prospects of development
Polowe detektory materiałów wybuchowych – stan aktualny i perspektywy rozwoju

Dariusz Augustyniak*), **Mateusz Szala**

Military University of Technology, 2 S. Kaliskiego St., Warsaw 00-908, Poland
** E-mail:* dariusz.augustyniak@wat.edu.pl

ORCID Information:
Augustyniak D.: 0009-0003-1191-3091
Szala M.: 0000-0002-6928-2689

Abstract: *A review of commercially available mobile detectors for the detection and identification of explosives was carried out. Seventy-three different mobile detectors, operating on five different analytical techniques, were identified. Most of these used ion mobility spectrometry (IMS) and infrared analysis techniques, i.e. FTIR, and Raman spectroscopy. Only three of the devices used two orthogonal analytical techniques which allow a significant improvement in the reliability of the analytical results. It was noted that colour or dye test kits based on the specific reaction of a given chemical reagent with the material being analysed are still very popular.*

Streszczenie*: Wykonano przegląd dostępnych rynkowo detektorów mobilnych do detekcji i identyfikacji materiałów wybuchowych. Zidentyfikowano 73 różne detektory mobilne pracujące w oparciu o 5 różnych technik analitycznych. Najwięcej zidentyfikowanych detektorów wykorzystuje spektrometrię ruchliwości jonów (IMS) oraz techniki analizy w podczerwieni czyli FTIR oraz spektroskopię Ramana. Tylko trzy z dyskutowanych urządzeń wykorzystują dwie ortogonalne techniki analityczne pozwalające znacząco podwyższyć wiarygodność uzyskiwanych wyników analiz. Zauważono, że nadal dużą popularnością cieszą się testy barwne oparte o reakcje charakterystyczne odpowiedniego odczynnika chemicznego z analitem.*

Keywords: *detection, detectors, analysis, field detection, field detectors, hazardous materials, explosives*
Słowa kluczowe: *detekcja, detektory, analiza, wykrywanie, detekcja polowa, detektory polowe, materiały niebezpieczne, materiały wybuchowe*

Abbreviations and acronyms

AN	Ammonium nitrate(V), NH_4NO_3
ANFO	Ammonium nitrate(V) mixed with diesel fuel
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosive
CW	Chemical weapon
DMNB	2,3-Dimethyl-2,3-dinitrobutane – a taggant used in explosives

EGDN	Ethane-1,2-diyl dinitrate (nitroglycol)
GA	(*RS*)-Ethyl *N*,*N*-dimethylphosphoramidocyanidate (tabun)
GB	Propan-2-yl methylphosphonofluoridate (sarin)
GD	3,3-Dimethylbutan-2-yl methylphosphonofluoridate (soman)
GF	Cyclohexyl methylphosphonofluoridate (cyclosarin)
HD	1-Chloro-2-[(2-chloroethyl)sulfanyl]ethane (sulphur mustard)
HMX	1,3,5,7-Tetranitro-1,3,5,7-tetraazacyclooctane (octogen)
IMS	Ion mobility spectrometry
L	2-Chlorovinyl-dichloroarsine, *bis*-(2-chlorovinyl)chloroarsine and *tris*-(2-chlorovinyl)arsine (lewisite)
MDMA	3,4-Methylenedioxymethamphetamine
NG	Propane-1,2,3-triyl trinitrate (nitroglycerine)
PCP	Phencyclidine
PETN	Pentaerythritol tetranitrate (pentrite)
RDX	1,3,5-Trinitro-1,3,5-triazacyclohexane, hexogen
SERS	Surface-Enhanced Raman Scattering
TATP	Triacetone triperoxide
THC	Tetrahydrocannabinol
TIC	Toxic industrial chemical
TIM	Toxic industrial material
TNT	2,4,6-Trinitrotoluene
U-47700	3,4-Dichloro-*N*-[(1*R*,2*R*)-2-(dimethylamino)cyclohexyl]-*N*-methylbenzamide – synthetic opiate drug
VX	*S*-{2-[Di(propan-2-yl)amino]ethyl} *O*-ethyl methylphosphonothioate

Units of concentration:

ppm	parts per million
ppb	parts per billion
ppt	parts per trillion

1. Introduction

The security of citizens in developed countries is one of the priorities of the military and law enforcement services. A state of war, being a state of emergency, has its own characteristics and the actions of the services are then highly visible, while security becomes an absolutely top priority, overriding economic growth and general welfare. During peace, the operation of military and law enforcement services – especially special services are not always public and therefore not visible to the general public. This condition is seen as beneficial, because potential adversaries of a country or nation, or ordinary criminals, are unaware of the potential and capabilities of the services tasked with the generally understood security of its nationals. In this context, dedicated tools such as portable hazardous material detectors are very important for the effectiveness of the services.

People are accustomed to tests or sweeps before boarding an airplane, carried out with metal detectors or Ion Mobility Spectrometry (IMS) detectors, while luggage is X-rayed to examine its contents. In the meantime, the array of dedicated explosive material detectors is very broad and includes nearly all analytical techniques known to professionals in chemistry. Due to design considerations, analytical techniques have varying miniaturisation potential, meaning some of them cannot be used in field applications, even in the 21st century.

An extensive review of field explosive material detection and identification equipment was performed. Explosive material detection equipment can be divided into scientific (stationary), portable and field detection equipment. In English there is a class of equipment called *handheld*, which usually corresponds to the Polish-language category of field equipment.

The scientific detection equipment has very powerful analytical capabilities but its operation requires highly skilled personnel, while generating a result can take days or even weeks. Portable devices are typically detection units adapted for transport at the expense of compromising their analytical capabilities. However, their proper performance requires the right conditions which are close to laboratory settings but not as stringent as those applied to traditional scientific instruments. Field devices usually have very limited analytical performance and are profiled for the specific group of chemical compounds being detected. This type of equipment is usually suitable for harsh environments and potential decontamination in accordance with relevant standards, e.g. [1]. Handheld devices must be compact enough to be carried and operated by one hand of an adult. This limits the weight of the device to approximately 5-7 kg.

The development of entertainment pyrotechnics has meant that explosive mixtures can be acquired without the applicable licenses simply because they are properly packaged and, if used correctly, should not be hazardous to health or life. These processes have resulted in the security services having to use increasingly sophisticated chemical detectors able to quickly identify a chemical substance or mixture which may be an explosive hazard.

This paper summarises current commercially available field explosive material detectors (FEMDs) and comparing them in terms of suitability for use by first responders to the suspected presence of explosive materials or ordnance. Due to the sheer number of FEMDs and the commercial availability of these devices operating using at least two analytical techniques, the classification of FEMDs in this paper is based on the type of analytical technique. Devices designed to offer orthogonal analytical techniques are discussed in separate sections. The most important detector specifications, provided by manufacturers/distributors, are tabulated. A ‘Substances detected’ column lists the specific explosives or group of chemical compounds as declared by the manufacturer. Other hazardous substances detectable by the FEMDs are provided. The review of FEMDs clearly showed that only a minority are dedicated solely to the detection of explosive materials. Manufacturers often specified the substances detected using acronyms or cryptonyms and these are quoted verbatim. Even if FEMDs prices were available in the reference literature or on dedicated websites, these were not included in this paper in order to prevent this leading to bias in the assessment of the FEMDs.

2. IMS

Attempts to build what is called an ‘artificial nose’ have been carried out for decades with the analytical technique with the greatest potential to mimic the sense of smell appearing to be IMS. The IMS technique involves the separation and identification of ions formed by ion-particle reactions in the gas phase based on the mobility of these ions in an electric field. The mobility of ions depends on their shape, charge and size. An IMS detector records the ion transit time and the result of an IMS test is a drift-time spectrum, being the function of ion current in time.

Due to the high potential for miniaturisation and the fact that omni-present water does not affect IMS tests as severely as in traditional mass spectrometry techniques, IMS is readily used in mobile detectors. An analysis of the market for mobile IMS detectors identified 15 devices, whose key performance parameters are listed in Table 1.

Table 1. Summary of key performance parameters in IMS FEMDs (CWs – chemical weapons, TICs – toxic industrial chemicals and TIMs – toxic industrial materials)

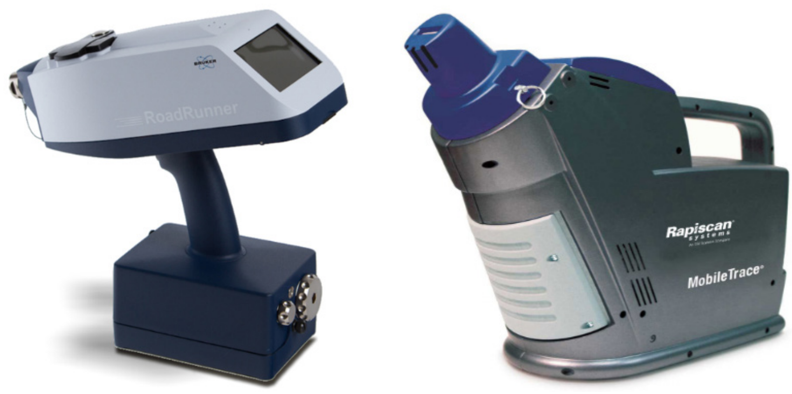
Manufacturer/ Designation	Substances detected				State of sample aggregation	Detection limits	Device weight [kg]	Ref.
	explosives/ narcotic substances	CWs	TICs/TIMs	others				
Seer Technology Inc./ Accu Sense	OK/ –	OK	OK	OK	Aerosol/gas	ppm; ppb	10.4	[2-4]
Scintrex Trace Corp./ E3500 Trace Detector	TNT, RDX, NG, AN, PETN, EGDN, HMX/ cocaine, opiates, THC, heroin, amphetamine-type stimulants, fentanyl, carfentanyl, sufentanyl, alfentanyl, remifentanyl, ketamine, lorazepam, 3-quinuclidinyl benzoate, U-47700	–	–	–	Aerosol/gas	ng	3.7	[5]
Leidos/ QS-H150 H150E	OK	–	OK	–	Aerosol/gas; Liquid/solid	ng	5	[6, 7]
Smith's Detection, Inc./ LCD 4 XID	OK/ –	OK	TICs	–	Aerosol/gas	ppm	0.58	[8]
Scintrex Trace Corp./ N2300 Trace Detector	TNT, RDX, NG, AN, PETN, EGDN, HMX, and UN/ cocaine, opiates, THC, heroin, amphetamine-type stimulants, fentanyl, carfentanyl, sufentanyl, alfentanyl, remifentanyl, ketamine, lorazepam, 3-3-quinuclidinyl benzylate, U-47700	–	–	–	Aerosol/gas	ng	3.2	[9]
Bruker Corporation/ RoadRunner	PETN, RDX, TNT, AN, urea nitrate, TATP, HMTD, NG, DMNB, EGDN/ cocaine, methamphetamine (METH), heroin, delta9-tetrahydrocannabinol 3,4-methylenedioxy-amphetamine, 3,4-methylenedioxy-N-methylamphetamine, lysergic acid diethylamide (LSD), fentanyl, carfentanyl, sufentanyl, alfentanyl, remifentanyl, ketamine, lorazepam, 3-quinuclidinyl benzoate, U-47700	–	–	–	Aerosol/gas	µg	3.5	[10]

Manufacturer/ Designation	Substances detected				State of sample aggregation	Detection limits	Device weight [kg]	Ref.
	explosives/ narcotic substances	CWs	TICs/TIMs	others				
Security Electronic Equipment Co.,Ltd./ SPE300	OK/ –	OK	OK	–	Aerosol/gas; Liquid/solid	ng, pg	4.3	[11]
NucTech Company Limited/ TR1000DB-A	OK	–	–	–	Aerosol/gas; Liquid/solid	ng	4	[12]
Smith's Detection, Inc./ Ionscan 600	OK/ –	OK	OK	–	Aerosol/gas; Liquid/solid	ng	10.8 (11.5 with printer)	[13]
Security Electronic Equipment Co., Ltd./ SPE9000 Series	OK	–	–	–	Aerosol/gas; Liquid/solid	ng	3	[14]
Owlstone, Inc./ Lonestar Portable Analyzer	DNT, DMNB, RDX, TNT/ –	OK	OK	–	Aerosol/gas	ppb	7.8	[15]
Inward Detection/ M-ION	TNT, RDX, PETN, ANFO, EGDN, NG, dynamite, DNT, black powder, nitrates, HMTD, tetryl and mixtures thereof	–	–	nitrates	Aerosol/gas	ppt	3	[16]
Rapiscan Systems/ MobileTrace	OK/ –	–	OK	–	Aerosol/gas	µg	4.3	[17]
Rapiscan Systems/ Hardened MobileTrace	TATP, peroxides, nitro compounds/ OK	OK	OK	–	Aerosol/gas	ppb, pg	5.44	[18]
Siebel/ MO-2M	TNT, RDX, NG, AN	–	–	–	Aerosol/gas	10^{-13} g/ cm^3	1.5	[19]

The world's leading analytical instrument manufacturers such as Bruker and Smith's Detection have entire product lines, but there are also many companies with smaller portfolios – or even start-ups and spin-offs offering just one instrument model. Although marketing brochures and data available on websites were mainly analysed, it was noted that the level of specification detail varies greatly. Few detectors indicate a specific chemical compound as the test result. More often, the result is an indication of the group or subgroup of chemical compounds in which the tested substance has been classified. Very often, the device only specifies the group of explosives to which the detected compound belongs. From a scientist's point of view, this is very vague information. However, it should be remembered that explosive material detectors are most often used by military or law enforcement services and information about a true-positive detection of an explosive is sufficient for an operator to initiate unexploded ordnance procedures. If another potentially hazardous substance is identified, the sample can be taken to a stationary laboratory for a detailed analysis by experts.

Today, manufacturers are increasingly departing from radioactive ionisation sources in IMS detectors. An example of such a portable IMS detector is Bruker's Road Runner (Figure 1(a)). The Road Runner uses a high-energy photon ionisation source. The manufacturer states that the use of patented CHIRP™ modulation technology provides greater detection sensitivity by increasing the signal-to-noise ratio. The detector's structure is IP42-rated against the ingress of solids and water. This means that the spectrometer unit is protected against solids with a diameter of 1 mm or more and water droplets incident at any angle up to 15° from vertical in all directions. What is missing is a statement of compliance with [1].

The development of mobile IMS detectors over the last few years has been geared towards discovering new design solutions to increase detection sensitivity. An interesting solution is offered by Rapiscan System in its Mobile Trace detector (Figure 1(b)). This detector uses IMS with ion trapping. An ion trap, in which ions are first trapped and then released in a controlled manner into the drift chamber where they are separated, has increased the sensitivity and selectivity of analysis. The manufacturer states that the device is IP54-rated, i.e. protected against ingress of dust and water from every direction. In addition, the design is [1] compliant. Rapiscan System provides 24/7 technical support via e-mail for the duration of the warranty period.



(a) (b)

Figure 1. Bruker Road Runner: a portable explosive material IMS detector [10] (a) and Rapiscan Systems Mobile Trace [18] (b)

Manufacturers state the detection limits for explosives in very different ways, so simply comparing FEMDs using this parameter is difficult. Most FEMDs detect nanograms of substance (ng); one manufacturer declaring picograms (pg) as the detection limit. Some suppliers characterise devices by specifying detection limits in the ppm, ppb and ppt ranges. Given the powerful capabilities of IMS and the use of modern programmable electronic units, the ranges given can be considered realistic. A separate issue is the selectivity of detection and identification, especially in mixtures. The declared mass of the FEMDs range from 0.58 to 10.8 kg. This wide range is due to several factors. The first is the FEMD's capabilities; the more generic information the device provides, the smaller the interface/display can be. The second factor is the peripherals and the size of the battery powering the FEMD. The third is the FEMD's resistance to external factors. Building a FEMD to a military standard usually results in an increase in mass.

3. Raman spectroscopy (RS)

In addition to the IMS instrument designs already discussed, Raman spectroscopy (RS) has become very popular in recent years in the construction of portable detectors. Advantage is taken of the fact that the Raman spectrum recorded in the 200-3000 cm^{-1} range is a kind of 'fingerprint' of the chemical compound of interest, which contributes to the rapid and reliable identification of chemicals.

RS is an attractive analytical technique in that no sample preparation is required, or only bare minimum preparatory steps are needed prior to analysis, with samples being tested in their natural condition, resulting in reduced analysis time. Given the sensitivity of explosives to external stimuli, this is clearly a huge advantage. In addition, RS enables non-invasive and non-destructive examination of samples, which is particularly important for small quantities of test specimens which can then be submitted for further laboratory testing. Another advantage is that samples can be analysed in different states - as liquids, solids, solutions, suspensions or pastes – and the measurement itself is not limited by a temperature or pressure range. An important aspect is that RS analyses can be performed through most transparent and translucent glass and plastic packaging materials without having to open them. RS devices usually feature a time delay to start the analysis. This feature is especially important when testing for explosives and thermosensitive materials. The excitation laser beam can cause inadvertent initiation of the explosive. Dark and solid-state materials are more thermosensitive due to their heat capacity, unlike liquids, which dissipate heat much faster. The measurement start delay setting allows the operator to ensure that safety procedures are complied with or to move to a safe distance. If the substance is suspected of being an explosive, it is recommended that a small sample is taken from the whole material and the analysis performed at a safe distance. Technological advances in recent years have enabled the construction of RS devices with the added functionality of a measurement range which can be up to several dozen centimetres. In this mode, some RS detector models require using dedicated optical terminals included with the device.

Over the last few years, there has been a rapid increase in commercially available handheld RS devices. As many detectors offer similar design and operational capabilities, Table 2 lists 36 RS FEMDs which the authors believe reflect market trends.

Table 2. Summary of key performance parameters for RS FEMDs

Manufacturer/ Designation	Substances detected				State of sample aggregation	Laser wavelength [nm]	Spectrum detection range [cm^{-1}]/ Resolution [cm^{-1}]/ Detection limit	Device weight [kg]	Ref.
	explosives and narcotic substances	CWs	TICs/TIMs	other					
Optosky Photonics Inc./ ATR6200	OK	OK	OK	–	Liquid/solid	785	250-2400/ 200-3300/ 13-15	1.2	[21]
Optosky Photonics Inc./ ATR6500/6600	OK	OK	OK	–	Liquid/solid	785/ 1064	200-4000/ 10/ 8-12	0.45/ 1.15	[22, 23]
Bruker Corporation/ Bravo	OK	OK	OK	–	Liquid/solid	700-1100	3200-300/ 10-12/ –	1.5	[24]
Coda Devices, Inc./ CDI 2	OK	OK	OK	–	Liquid/solid	785	500-1800/ 6-8/ –	3	[25]
Anton Paar USA, Inc./ Cora 100	OK	OK	OK	–	Liquid/solid	785	400-2300/ 10/ –	0.65	[26]
Rigaku Analytical Devices/ CQL Gen-ID	OK	OK	OK	–	Liquid/solid	1064	200-2500/ 6-13/ –	1.7	[27]
Rigaku Analytical Devices/ CQL Max-ID	OK	OK	OK	OK	Liquid/solid	1064	200-2500/ 6-13/ –	1.7	[28]
Thermo Fisher Scientific Inc./ FirstDefender RM	OK	OK	OK	OK	Liquid/solid	785	250-2875/ 7-10.5/ –	0.8	[29]
Thermo Fisher Scientific Inc./ FirstDefender RMX	OK	OK	OK	OK	Liquid/solid	785	250-2875/ 7-10.5/ –	0.919	[30]
RS DYNAMICS/ microRAMAN	OK	OK	OK	OK	Liquid/solid	785	200-2000/ 12/ –	0.65	[31]
RS DYNAMICS/ miniSPECTRE	OK	OK	OK	OK	Liquid/solid	785	400-2300/ 8-10/ ng	0.95	[32]
Metrohm/ MIRA DS/ XTR DS	OK	OK	OK	OK	Liquid/solid	785	–/ –/ mg	2.5	[33]

Manufacturer/ Designation	Substances detected				State of sample aggregation	Laser wavelength [nm]	Spectrum detection range [cm^{-1}]/ Resolution [cm^{-1}]/ Detection limit	Device weight [kg]	Ref.
	explosives and narcotic substances	CWs	TICs/TIMs	other					
Metrohm/ NanoRam	OK	OK	OK	OK	Liquid/solid	785	176-2900/ –/ mg	1.2	[34]
	–					1064	176-2500/ –/ mg		
Pendar Technologies/ Pendar X10	OK	OK	OK	OK	Liquid/solid	1064	200-2000/ 12/ mg	2.0	[35]
Chemring Detection Systems/ PGR-1064	OK	OK	OK	OK	Liquid/solid	1064	350-1850/ 8/ mg	1.0	[36]
Agiltron/ PinPointer	OK	OK	OK	OK	Liquid/solid	785	200-3000/ 9/ –	1.4	[37]
Rigaku Analytical Devices/ Progeny	OK	OK	OK	OK	Liquid/solid	1064	200-2500/ –/ –	1.6	[38]
BioTools/ RamTest	OK	OK	OK	OK	Liquid/solid	532	100-4000/ 4-6/ –	2	[39]
Agilent Technologies/ Resolve Handheld SORS	OK	OK	OK	OK	Liquid/solid	830	350-2000/ 10/ mg	2.2	[40]
NucTech Company Limited/ RT6000S	OK	–	OK	–	Liquid/solid	1550	/ –/ –/ –	0.47	[41]
Serstech/ Serstech 100 Indicator	OK	OK	OK	–	Liquid/solid	785	400-2300/ –/ –	0.65	[42]
StellarNet/ StellarRAM	OK	OK	OK	–	Liquid/solid	785/ 1064	200-2250/ 12/ –	2.5	[43]
Metrohm/ TacticID Series	OK	OK	OK	–	Liquid/solid	1064	179-2900/ 9/ –	0.9	[44]
Thermo Fisher Scientific Inc./ TruScan RM	OK	OK	OK	–	Liquid/solid	785	250-2875/ 8-10.5/ –	0.9	[45]
Agilent Technologies/ Vaya	OK	OK	OK	–	Liquid/solid	830	350-2000/ –/ –	1.6	[46]
Horiba Scientific/ AnywhereRaman	OK	OK	OK	–	Liquid/solid	785	150-3150/ 5-6/ –	3.6	[47]

Manufacturer/ Designation	Substances detected				State of sample aggregation	Laser wavelength [nm]	Spectrum detection range [cm^{-1}]/ Resolution [cm^{-1}]/ Detection limit	Device weight [kg]	Ref.
	explosives and narcotic substances	CWs	TICs/TIMs	other					
Coda Devices Inc./ CDI 1M	OK	OK	OK	–	Liquid/solid	785	(500-1800; 300-2900)/ (6-8; 8-9)/ –	11	[48]
Metrohm/ IM-52	OK	–	–	–	Liquid/solid	785	200-3200/ 4-8/ –	10	[49]
InPhotonics Inc./ InPhochelle	OK	OK	OK	–	Liquid/solid	670/785	100-3500/ 2/ –	7.7	[50]
InPhotonics Inc./ InPhotote	OK	OK	OK	OK	Liquid/solid	785	250-2350/ 2/ mg	10	[51]
Metrohm/ i-Raman/ Raman Prime	OK	OK	OK	OK	Liquid/solid	785	(150-4000; 50-3300; 150-3200; 150-2700)/ –/ mg	3	[52]
Optosky Photonics Inc./ Portable Raman Analyzer Series	OK	OK	OK	OK	Liquid/solid	473/532/785/ 830/1064	50-4000/ 19/ mg	7.5	[53]
Alakai Defense Systems/ PRIED	OK	OK	OK	OK	Liquid/solid	262	400-2000/ <10/ mg	2.9/ 14 (backpack form factor)	[54]
Advanced Nano Technologies/ Raman Flipper	OK	OK	OK	OK	Liquid/solid	638	270-2400/ 6/ ng	7.1	[55]
						785	270-2000/ 6/ ng		
						830	200-1850/ 6/ ng		
						1064	250-1850/ 6/ ng		
Agilent Technologies/ RapID	OK	OK	OK	OK	Liquid/solid	830	–/ –/ ~10%	47	[56]
StellarNet/ StellarCASE-Raman	OK	OK	OK	OK	Liquid/solid	785	200-2300/ 4/ –	5.4	[57]

A review of the range of available RS devices on the market leads to the conclusion that the differences between the various detectors lie in their size, excitation laser frequency, optical system solutions, measurement range, and resolution.
Many manufacturers do not declare a detection limit, but it is nevertheless noted in the following list that if one is declared, it is at levels ranging from mg to ng as in the case of detectors from Metrohm, Agilent Technologies (Figure 2), InPhotonics Inc. or Alakai Defense Systems. It is generally possible to find a performance specification by the manufacturer, such as the spectral detection range, laser wavelength or resolution of the detected spectrum. As for the physical characteristics of the devices, handheld RS FEMDs weighing from a few hundred grams to several kilograms are generally found, as in the case of the devices from Bruker Corporation, Rigaku Analytical Devices (Figure 3), Thermo Fisher or Metrohm. Less common are portable spectrometers in 'suitcase' form. Their weight can be as much as several kilograms as in the case of FEMDs from Coda Devices Inc. (Figure 4), InPhotonics Inc. or Optosky Photonics Inc. The last type are FEMDs which can be mounted on trolleys or mobile rigs typically used in the field; examples include RS detectors from Advanced Nano Technologies and Agilent Technologies (Figure 5). Based solely on the performance parameters declared by the manufacturers, it is difficult to explicitly indicate which of the FEMDs listed in the table is best for field detection and identification of explosives. The widest spectral range combined with the best resolution of detected spectra is provided by the InPhochelle FEMD from InPhotonics Inc. (Figure 6).

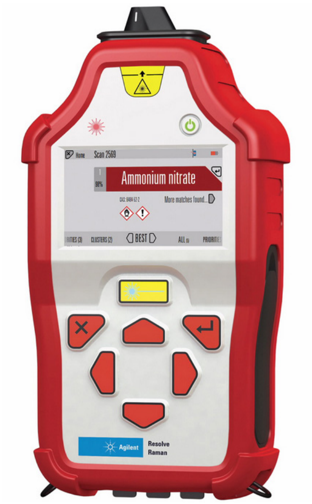


Figure 2. Resolve Handheld SORS by Agilent Technologies [40]

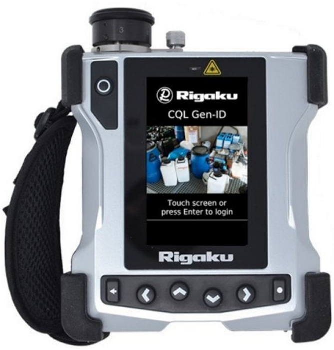


Figure 3. CQL Gen-ID RS detector by Rigaku Analytical Devices [27]

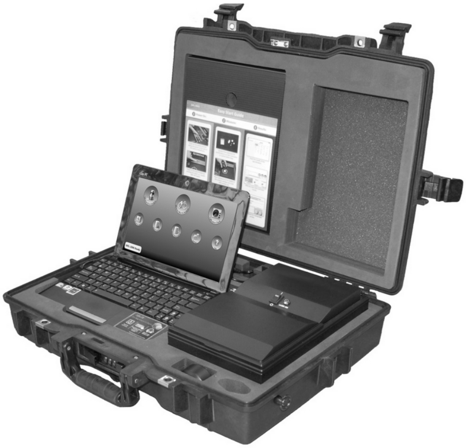


Figure 4. CDI 1M RS detector by Coda Devices [48]

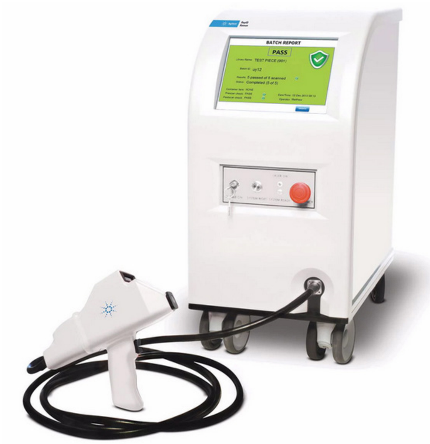


Figure 5. RapID RS detector by Agilent Technologies [56]

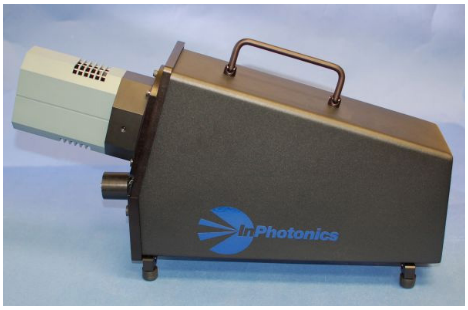


Figure 6. InPochelle RS detector by InPhotonics [50]

In recent years, manufacturers have been working on the implementation of measurement techniques such as surface-enhanced Raman scattering (SERS), spatially offset Raman spectroscopy (SORS), or low-frequency Raman spectroscopy (LF-Raman), among others [20].

4. Surface-Enhanced Raman Scattering (SERS)

SERS allows the application of RS to be extended to trace analysis of explosives. SERS can identify both biological and chemical substances by increasing the signal-to-noise ratio (S/N) by up to a million times. SERS is based on the optical properties of nanostructured substrates which contain metals. The most commonly used are gold and silver; others found in use in SERS include copper, platinum and palladium. A sample of the analysis sample is applied to suitably prepared substrates and, as a result of interaction with the substrate during measurement, feeds back an enhanced signal in the spectrometer. Nevertheless, it should be noted that the test result obtained depends on the wavelength of the excitation laser, the radiation range and the resolution [58]. The detection result relies heavily on the SERS substrate materials. Two lines of research are found in the literature on SERS. One is the testing of commercially available SERS substrates and the other is the research work at scientific centres on new SERS substrates to enhance the analytical capabilities of this technique [59]. From a review of references in terms of the current range of commercially available SERS-dedicated substrate solutions, Thermo Fisher comes to the fore in available materials indicating intensive research into expanding the range of SERS substrate solutions [60-63]. It should be noted that Thermo Fisher offers SERS-driven solutions dedicated to the DXR3 Raman family of desktop RS detectors. Other examples of commercially available SERS substrates are provided by SERSitive, OceanOptics, Nikalyte, and Hamamatsu Photonics [64-67].

Observing the dynamic increase in the availability of mobile RS detectors offering a variety of technical solutions, development of SERS substrates, as well as research into SERS substrate usability under field conditions, will be continued by both leading manufacturers and research centres focusing on the detection and identification of hazardous substances under non-laboratory conditions, where the ease of performing a comprehensive determination is of particular importance.

5. Infrared spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) typically uses electromagnetic radiation in the 400-4000 cm^{-1} range and is a complementary technique to RS. Functional groups of chemical molecules absorb infrared radiation in a narrow frequency range, resulting in changes to the rotational and oscillatory energy of the molecule. As a result, absorption spectra can be detected, the complexity of which preclude the reading of identical spectra for different compounds. By analysing the spectrum obtained or comparing it to the library stored in the FTIR spectrometer, it is possible to identify the tested substance. Currently, most FTIR detectors use multiple ATR (Attenuated Total Reflectance). As a result, it is sometimes possible to see the designation FTIR-ATR in the reference literature provided by detector manufacturers. ATR uses the phenomenon of total reflectance. In ATR, infrared radiation is directed through a crystal onto the sample. The infrared radiation only interacts with a sample layer a few micrometres thick and then passes back through the crystal, enabling detection and reading. The most commonly used materials are germanium and diamond crystals. ATR enables the analysis of solutions whose components exhibit very strong absorption bands of their own. FTIR spectrometers are the third most common group of FEMDs. In Table 3, eight FTIR spectrometers are listed, representing the solutions currently provided by leading manufacturers as well as smaller businesses. There is a noticeable convergence when it comes to the operational performance of the FEMDs, such as infrared range and resolution. Depending on their intended use, the FEMDs available on the market have design solutions for testing samples in the gaseous, liquid or solid state. Different miniaturisation levels can be found for this group of FEMDs. The handiest solutions are offered by Thermo Fisher in the form of its two flagship detectors: TruDefender FT and TruDefender FTX (Figure 7). The analytical capabilities of both models are similar.

Figure 7. TruDefender FTX FTIR spectrometer by Thermo Fisher [72]

However, they differ in design, the FTX model being a newer and improved version of the FT model developed based on (according to the manufacturer) feedback from users of the legacy FEMD. The TruDefender FTX model has been developed for military and law enforcement use and complies with the military requirements specified in [1]. Worth noting is the ease of maintenance of the device, which requires no calibration, warm-up or adjustment of mirrors, and features no wearable parts. An important distinguishing aspect of this FEMD is its decontamination capability. The TruDefender FTX can be immersed in a decontaminant or other cleaning product and dried to become reprocessed and ready for continued service.

Another FTIR spectrometer compliant with [1] is Smith's Detection HazMatID Elite (Figure 8). The FEMD is heavier and less portable, but nevertheless offers similar detection capabilities to those of the TruDefender FTX. The manufacturer states that the detector can be used in harsh conditions and high temperatures, but does not provide detailed specifications of the decontamination process.

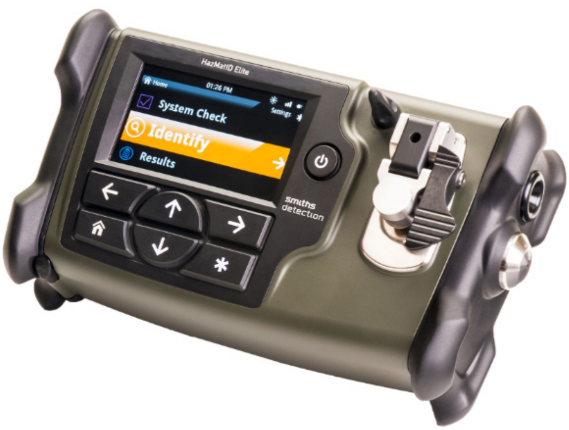


Figure 8. HazMatID Elite FTIR spectrometer by Smith's Detection [69]

A handheld and suitcase solution is provided by Agilent Technologies; these are the 5500 Series Compact FTIR (Figure 9) and the 4500 Series Portable FTIR. These FEMDs are small platforms which enable analysis in non-laboratory conditions. The design of these FEMDs tends to rule out use by military or law enforcement, where time to analytical results and handheld portability are crucial. Nevertheless, they could find use, for example, as instruments for mobile laboratories. RedWave Technology also has a suitcase version in its product portfolio, the ThreatID FEMD (Figure 10). It allows gaseous, liquid and solid samples to be tested at ppm) levels.

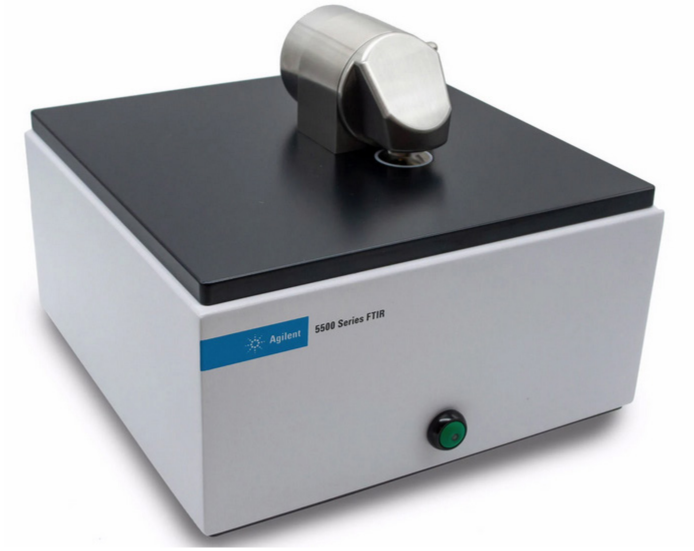


Figure 9. 5500 Series Compact FTIR spectrometer by Agilent Technologies [74]

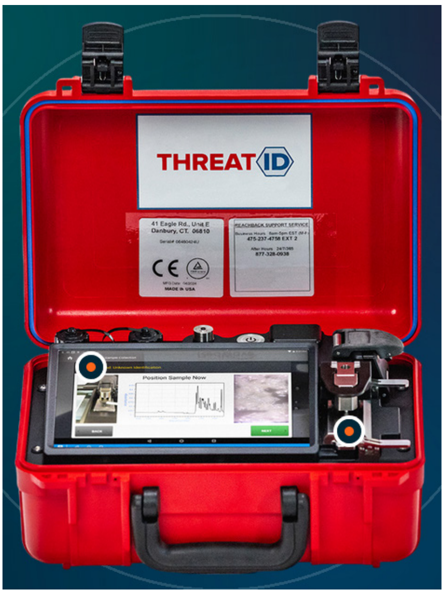


Figure 10. ThreatID FTIR spectrometer by 908 Devices [75]

Table 3. Summary of key performance parameters for mobile and handheld FTIR FEMDs

<table>
<tr><th rowspan="2">Manufacturer/ Designation</th><th colspan="3">Substances detected</th><th>State of sample aggregation</th><th>Spectrum detection range [cm⁻¹]/ Resolution [cm⁻¹]</th><th>Device weight [kg]</th><th>Ref.</th></tr>
<tr><th>explosives and narcotic substances</th><th>CWs</th><th>TICs/TIMs</th><th></th><th></th><th></th><th></th></tr>
<tr><td>Agilent Technologies/ 4300 Handheld FTIR Spectrometer</td><td rowspan="8">OK</td><td rowspan="3">OK</td><td rowspan="8">OK</td><td>Aerosol/gas; Liquid/solid</td><td>5200-650/ 4-16</td><td>2.2</td><td>[68]</td></tr>
<tr><td>Smith's Detection, Inc./ HazMatID Elite</td><td rowspan="6">Liquid/solid</td><td>4000-650/ –</td><td>2.29</td><td>[69]</td></tr>
<tr><td>RedWave Technology, LLC/ ProtectIR</td><td>4000-650/ –</td><td>2.3</td><td>[70]</td></tr>
<tr><td>Thermo Fisher Scientific, Inc./ TruDefender FT</td><td rowspan="2">OK*)</td><td>4000-650/ 4</td><td>1.3</td><td>[71]</td></tr>
<tr><td>Thermo Fisher Scientific, Inc./ TruDefender FTX</td><td>4000-650/ 4</td><td>1.41</td><td>[72]</td></tr>
<tr><td>Agilent Technologies/ 4500 Series Portable FTIR</td><td rowspan="3">OK</td><td>4000-650/ 2-32</td><td>6.8</td><td>[73]</td></tr>
<tr><td>Agilent Technologies/ 5500 Series Compact FTIR</td><td>4000-650/ 2-32</td><td>3.6</td><td>[74]</td></tr>
<tr><td>RedWaveTechnology, LLC/ ThreatID</td><td>Aerosol/gas; Liquid/solid</td><td>–**)</td><td>6.3</td><td>[75]</td></tr>
</table>

*) GA, GB, GD, HD, HNs, VX, other, **) 25 ppm

6. Mass spectrometry (MS)

MS is a technique most often combined with gas chromatography, which offers very high analytical capability while allowing separation of components in mixtures. The combination of these two techniques has colloquially taken root as the acronym GCMS (Gas Chromatograph Mass Spectrometer). The mixture of compounds to be analysed is first separated in a gas chromatograph, which provides a chromatogram. In the mass spectrometer, the separated chemical compounds are ionised and the resulting ions are separated according to their mass-to-charge ratio (m/z). The result is a recorded mass spectrum, reading the levels of the signals as a function of mass to ion charge ratio. The chemical compound undergoes a specific fragmentation by ionisation, generating a characteristic mass spectrum which enables its identification.

A number of advantages of these two techniques when combined, have contributed in recent years to attempts in developing a portable detector providing similar detection capabilities to stationary GCMS instruments. Market availability of GCMS is limited compared to FEMDs operating using RS or FTIR spectroscopy. Table 4 lists commercially available mobile GCMS explosive material detectors. Undoubtedly, the Griffin G510 from Teledyne FLIR (Figure 11) stands out from the other FEMDs listed.

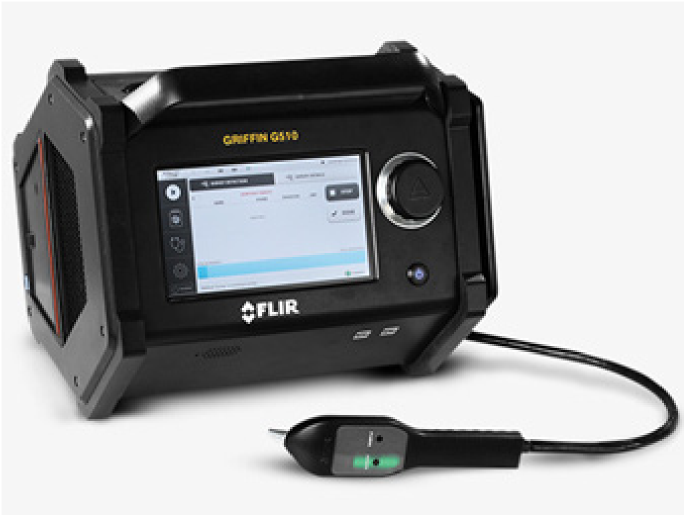
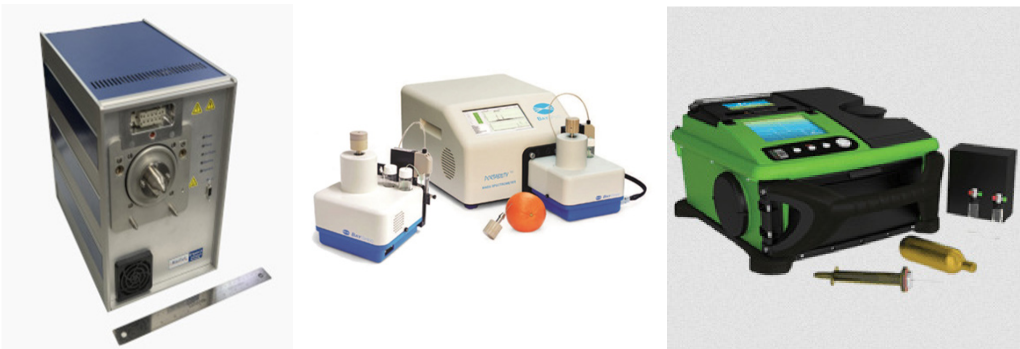


Figure 11. Griffin G510 coupled gas chromatograph/mass spectrometer from Teledyne FLIR [76]

The instrument is capable of analysing samples in all states of aggregation. In addition to the heated probe for gas detection, the device enables injection of the sample into the mass spectrometer through the use of a split/splitless dispenser which is included. The Griffin G510 uses a quadrupole mass spectrometer allowing detection in the 15-515 m/z range with a limit of ppb for gases and aerosols, and ng for liquid and solid samples.

An ion trap mass spectrometer is used in three FEMDs: Torion T-9, Portability™ Transportable Mass Spectrometer, and Explorer 30. The design of the Torion T-9 stands out from the other two mass spectrometers in terms of field applications. The Torion T-9 uses fibres for solid-phase microextraction (SPME), capillary microextraction or needle trap as the sample introduction system.

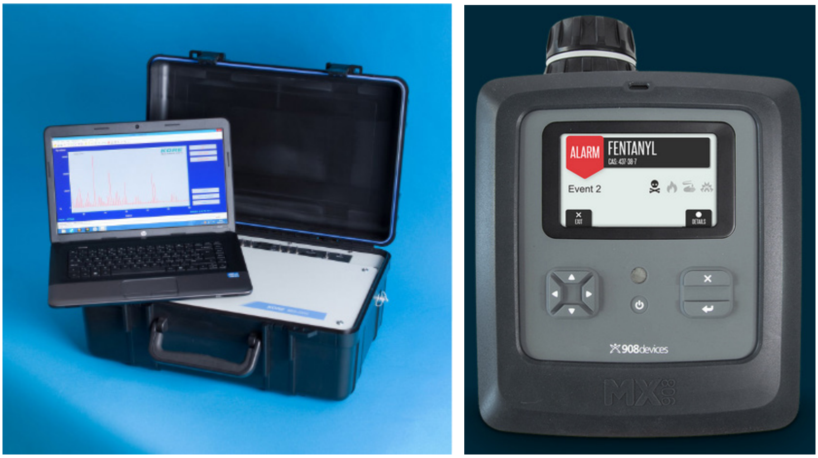
The Portability™ Transportable Mass Spectrometer and MT Explorer 30, developed for testing outside of laboratories, have peripherals which significantly limit their mobility in the field. Compatible with most ionisation sources, BaySpec's Portability enables the detection of substances in any state of aggregation with a resolution in ppt.



(a) (b) (c)

Figure 12. MT Explorer 30 [79] (a), Portability Transportable Mass Spectrometer [80] (b) and Mass spectrometer Torion T-9 [81] (c)

Another type of mobile mass spectrometer is the time-of-flight analyser (Time of Flight Mass Spectrometer, TOF-MS), which is used in the Kore MS-200 from Kore Technology. The Kore MS-200 is designed to identify gases and vapours of hazardous substances at a ppb resolution level. The device's suitcase form makes it heavier when compared to other FEMDs. This can be offset by an increased mass range of detected chemical molecules, 1 to 1000 m/z.



(a) (b)

Figure 13. Mass spectrometers: Kore MS-200 (a) [77] and MX908 [78] (b)

The last of the portable MS detectors is the MX908 from 908 Devices, using high-pressure mass spectrometry. According to the manufacturer, the state of sample aggregation is irrelevant. Gas/aerosols can be analysed continuously while liquid and solid samples can be processed using swabbing papers supplied by the manufacturer. The MX908 detects explosives at a limit down to ppb. The design of the device is [1] compliant.

Table 4. Summary of key performance parameters of GC-MS FEMDs

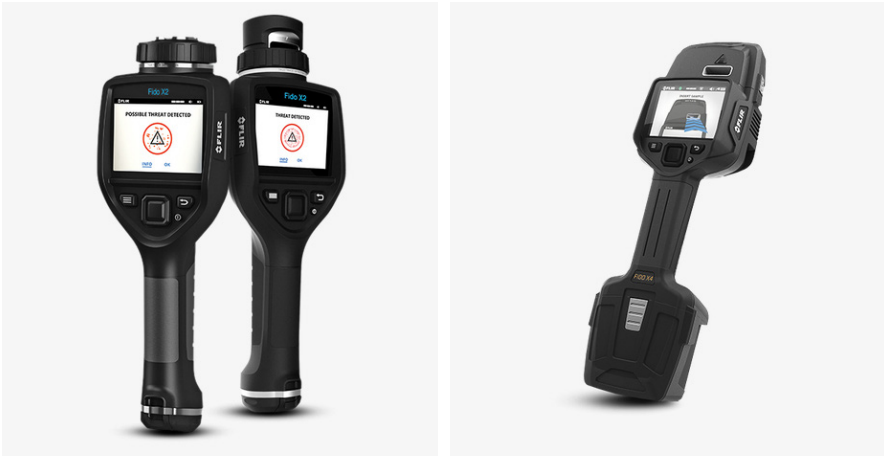
<table>
<tr><th rowspan="2">Manufacturer/ Designation</th><th colspan="4">Substances detected</th><th rowspan="2">State of sample aggregation</th><th rowspan="2">Detection limit/ Mass range</th><th rowspan="2">Device weight [kg]</th><th rowspan="2">Ref.</th></tr>
<tr><th>explosives and narcotic substances</th><th>CWs</th><th>TICs/TIMs</th><th>other</th></tr>
<tr><td>Teledyne FLIR Detection, Inc./ Griffin™ G510</td><td rowspan="2">OK</td><td rowspan="2">OK</td><td rowspan="6">OK</td><td rowspan="2">OK</td><td>Aerosol/ gas; Liquid; Solid</td><td>ppm, ppb, ng/ 15-515 m/z</td><td>16.3</td><td>[76]</td></tr>
<tr><td>Kore Technology Ltd./ KoreMS-200</td><td>Aerosol/gas</td><td>ppb/ 1-1000 m/z</td><td>23</td><td>[77]</td></tr>
<tr><td>908 Devices, Inc./ MX908</td><td>OK*)</td><td>OK**)</td><td>OK***)</td><td>Aerosol/ gas/vapors; Liquid; Solid</td><td>ppb, ng, µg/ –</td><td>4.3</td><td>[78]</td></tr>
<tr><td>MassTech/ MT Explorer 30</td><td rowspan="3">OK</td><td rowspan="3">OK</td><td rowspan="3">OK</td><td>Aerosol/gas</td><td>pg, ng/ (30-2000; 0.5 amu)</td><td>16</td><td>[79]</td></tr>
<tr><td>Bay Spec/ Portability™ Transportable Mass Spectrometer</td><td>Aerosol/ gas/vapors/ liquid; Solid</td><td>ppt/ (50-600; 0.49 amu)</td><td>10</td><td>[80]</td></tr>
<tr><td>Perkin Elmer/ Torion T-9</td><td>Aerosol/gas; Liquid</td><td>ppb 41-500 m/z</td><td>14.5</td><td>[81]</td></tr>
</table>

*) ETN, HMTD, HMX, MEKP, PETN, RDX, TNT, TATP and others, **) A, HD, GA, GB, GD, GF, VX, ***) 50-460 amu

7. Laser-induced fluorescence (LIF)

LIF, categorised as a spectroscopic technique, involves the excitation of a chemical compound molecule by the absorption of laser light. This results in the emission of light (fluorescence) from the molecules within a very short time after excitation. The emitted light has a longer wavelength than that of the excitation laser, making it easier to detect. The result is a fluorescence spectrum as a function of intensity vs. wavelength, the analysis of which provides insights into the test specimen. A specific substance is detected easier by the fact that every chemical compound has a unique fluorescent spectrum.

Teledyne FLIR Detection has a portfolio of mobile detectors using Amplifying Fluorescence Polymers (AFP) during irradiation with a laser (usually a diode one). The FidoX2 and FidoX4 are designed to identify explosives. The result is obtained in a maximum of 10 s and the lower detection limit for both models is reported to be at the nanogram level. In these FEMDs, detection is carried out in a non-obvious way, as the laser beam first impinges the photopolymer, which undergoes excitation by which it emits characteristic radiation. Vapours of the compound to be detected lie in the path between the laser source and the photopolymer resulting in a perturbed spectrum of the photopolymer, the analysis of which is the sole basis of the detection process. The manufacturer states that the sampling strips are reusable. The FidoX4 features a [1] compliant design.



(a) (b)

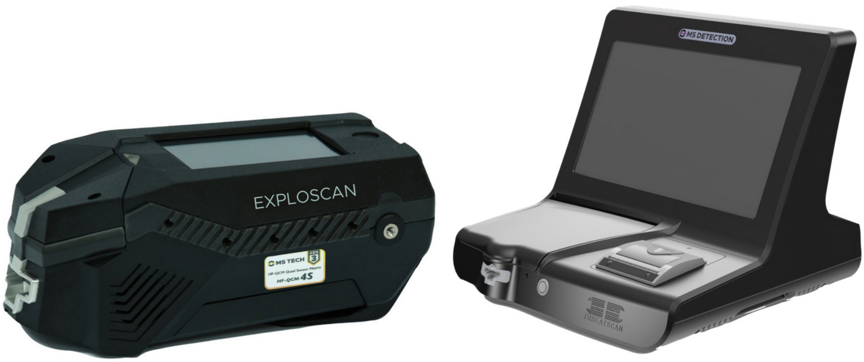
Figure 14. Mobile FEMDs: FidoX2 [82] (a) and FidoX4 [83] (b)

Table 5. Summary of key performance parameters of AFP FEMDs from Teledyne FLIR Detection, Inc.

Designation	Explosives detected	State of sample aggregation	Detection limits	Device weight [kg]	Ref.
FidoX2	Military explosives, nitrates, peroxides	Liquid; Solid	ng	0.7	[82]
FidoX4	Nitroamines, nitrate esters, nitrosoamines, inorganic nitrates, plastic explosives, low-smoke low explosives and peroxides			1.5	[83]

8. Quartz crystal microbalance (QMB)

In recent years, there has been a growing interest in the feasibility of sensor applications based on a QMB. Here, the detection process is based on varying the oscillator frequency when an additional chemical compound is present in the air being scanned. This method is currently being developed by MS Technologies. Table 6 shows commercially available QMB mobile detectors. The Exploscan (Figure 15(a)), available in civilian and military versions, is a FEMD which enables detecting military, plastic and improvised explosives.



(a) (b)

Figure 15. Mobile FEMDs from MS Technologie: Exploscan [84] (a) and Threatscan [86] (b)

The FEMD uses high-frequency QMB sensors. The advantage is that there is no carrier gas or radiation source. The FEMD allows the identification of vapours of substances present in the air during continuous air aspiration from the surface using the swabs included with the device. The analysis time is approximately 7-15 s and the detection limit is at the nanogram level for liquid and solid samples and at ppb for vapours. An extended detection range for synthetic drugs including fentanyl derivatives is provided by the Duoscan and Multiscan detectors. The Liquidscan detector, on the other hand, is designed for the detection of liquid explosives and their precursors, narcotic substances and toxic industrial chemicals. The last - and much larger - detector in this family is the Threatscan (Figure 15(b)). As part of the Antevorta Emergency Operations Centre, MS Technologies pledges 24/7 support, staffed by experts with extensive knowledge of explosives. Thus, from a practical point of view, the FEMD operator has the option of sending a debatable result, which can be immediately assessed by the experts.

Table 6. Summary of QMD FEMDs

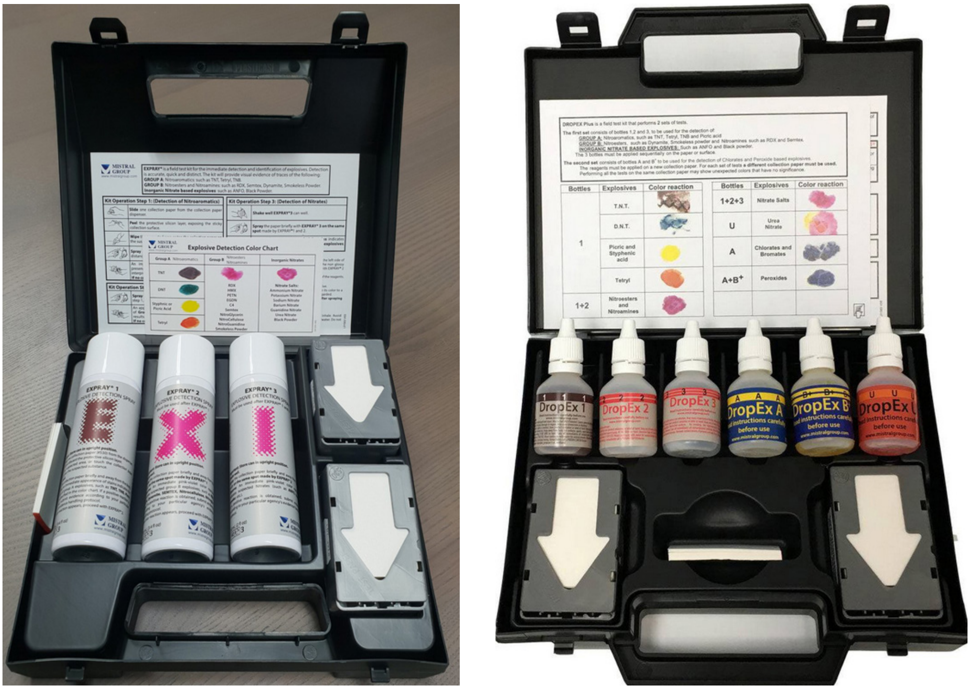
Manufacturer/ Designation	Substances detected	State of sample aggregation	Detection limits	Device weight [kg]	Ref.
MS Technologies Inc./ Exploscan/ Duoscan/Multiscan	Explosives; Narcotic substances	Aerosol/gas; Liquid/solid	ng, ppm	0.85	[84]
MS Technologies Inc./ Liquiscan	Explosives; TICs/TIMs	Aerosol/gas; Liquid; Solid		0.66	[85]
MS Technologies Inc./ Threatscan	Explosives; Narcotic substances			10	[86]

9. Characteristic colour reactions

Colour or dye test kits use a characteristic chemical reaction involving a change in colour when the chemical or group of compounds being determined comes into contact with the chemical reagents contained in a specific colorimetric test. A wide range of dye test kits for individual CBRNE agents is commercially available. The colour change is interpreted by the operator who uses colour reference charts most often included in the instructions supplied with the test kit. It should be noted that the operator's reading of colour can be highly subjective being affected by visual impairment, conditions for reading the display, light intensity, operator fatigue and a too low analyte concentration. Commercially available electronic readers, called 'colorimeters', enable digital objectification of the colour change produced (by analysing the characteristic bands in the UV-VIS range), thus reducing the possibility of operator error. The detection limit of colour tests in most cases is ppm, µg, rarely ng.

9.1. Operator-detected colour reactions

Selected examples of commercially available colour test kits are listed in Table 7. As a large number of different colorimetric tests is available, the summary provides examples of each typical test solution. Colour tests in spray form enable fast and effective identification of explosives. A spray colour test is performed by applying and rubbing the surface on which a potentially hazardous substance is present, with a strip from the test kit. The strip is then sprayed with the analyte and, once the colour appears, the reading is taken by comparing it to the included reference scale. An example of such a test kit is Mistral Security's Expray (Figure 16(a)). An analyte dropper -instead of an analyte spray -is featured in the DropEx Plus test kit for the detection of explosives and their precursors (Figure 16(b)).



(a) (b)

Figure 16. Expray spray colour test kits (a) [87] and DropEX explosive detection test kit (b) [89]

Commercially available test kits exist for the detection of a wide range of hazardous materials, including explosives. An example is the solution offered by Haztech Systems, Inc. The test kit is called HazCat 2.0 Pro and is designed for field testing (Figure 17). It includes a range of reagents, colour tests as well as accessories for test result evaluation. The included procedures explain its use.

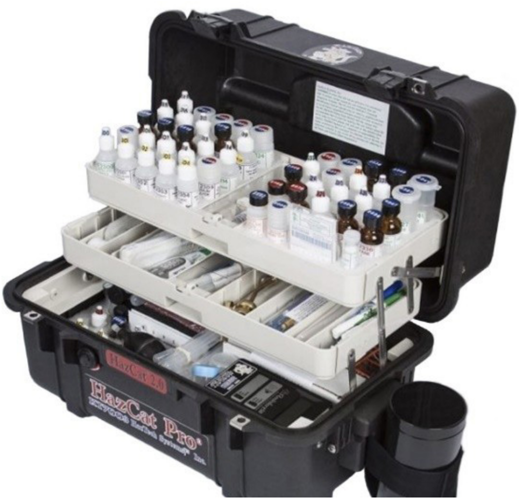


Figure 17. HazCat 2.0 colour test kit for hazardous material identification

Table 7. Summary of colour test kits for explosive material detection and identification

Manufacturer/ Designation	Substances detected	State of sample aggregation	Detection limits	Device weight [kg]	Ref.
Mistral Security, Inc./ Expray	Explosives	Liquid; Solid	ng	0.45	[87]
Serim Research Corporation/ Discern® HME Detection Kit	Explosives (AN, urea nitrate, oxidisers like chlorates, bromates, perchlorates and peroxides (hydrogen peroxide, HMTD, TATP))	Liquid; Solid	µg; ppm	–	[88]
Mistral Security, Inc./ DropEx Plus Explosive Detection Kit	Explosives (TNT, PETN, RDX, HMX, chlorates/ superchlorates)	Liquid; Solid	ng	0.45	[89]
Field Forensics, Inc./ ELITE Test Kit Series	Explosives (AN, TNT, RDX, HMX, PETN, EGDN; all explosives based on nitrates, peroxides, chlorates and perchlorates)	Liquid; Solid		2.3	[90]
Mistral Security, Inc./ ExPen	Explosives (TNT, RDX, HMX, PETN, AN, chlorates, perchlorates)	Liquid; Solid		0.9	[91]
Haztech Systems, Inc./ HazCat 2.0 Pro	Explosives, CWs (G-series, V-series, GV-series, DC, DF, QL, chlorosarin, carbamates, sulphur-based (HD, T, Q), arsenic-based, nitrogen-based (HN), key precursors); TICs/TIMs; Narcotic substances (opiates (morphine, codeine, heroin,) brown heroin, demerol, LSD, amphetamine, methamphetamine, MDMA, cannabis, hashish, hash oil, cocaine, crack, PCP, ephedrine); Biological weapons (anthrax, ricin, botulinum toxin, plague, brucellosis, tularemia, orthopoxvirus); Radiological	Liquid; Solid	ppm; mg	11.8	[92]
IDenta Corp./ IDenta Drug and Explosives Test Kits	Explosives; TICs/TIMs (urea nitrate, AN, TATP); Narcotic substances (cocaine, heroin, marijuana, LSD, synthetic cannabinoids and cathinones, ecstasy, methamphetamine, amphetamine, ketamine, GHB, barbituates, flunitrazepam, morphine, PCP, mandrax, mephedrone, fentanyl, paracetamol, methadone)	Liquid; Solid	trace residues	0.040	[93]
Field Forensics, Inc./ Spot.On.ID™	Explosives (RDX, PETN, TNT); Narcotic substances	Liquid; Solid	ng	13.6	[94]

Some of the easiest to use are the tests commonly known as 'ampoule tests'. An example of this is provided by IDenta Corporation. The test kit consists of an integrated sampler to acquire the test specimen, which is next moved to a test cell. The chemical reaction is triggered by crushing the ampoule containing the chemical reagent; this reaction being visually monitored for a colour change which can be compared to a reference colour chart. A similar solution is provided by Field Forensics, being its ELITE Test Kit Series. A colour change in the test indicates the group of explosives to which the tested substance belongs.
Thin-layer chromatography (TLC) is used in the Spot.On.ID test kit which is feasible for field and laboratory environments. The test kit allows separation and identification of tested substances which cannot be differentiated using colorimetric tests. The solution is an alternative between simple colour test kits and analytical techniques. The nanogram-resolution detection of explosives and narcotic substances, and the fact that the plates and sampler (the Spotter) can undergo additional analysis in the laboratory, are undisputed advantages of the Spot.On.ID test kit.

9.2. Objective colour change observation colorimeters

Misinterpretation of the colour change in a colour test can be countered by using commercially available portable colorimeters. Table 8 features DetectaChem's SEEKERe colorimeter which, in combination with proprietary detection cards, enables the detection of explosives (Figure 18). The SEEKERe only allows an initial qualification of the explosive group that the operator has encountered.

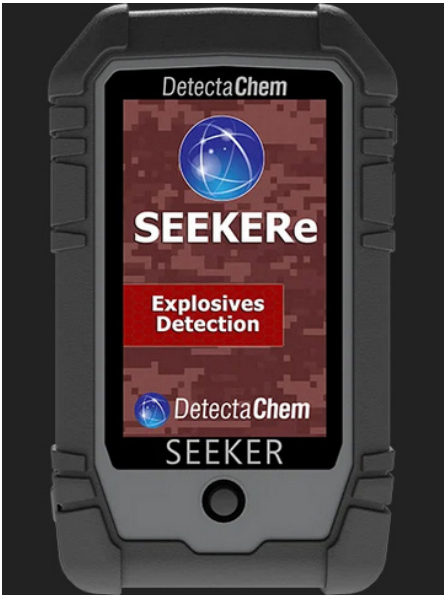


Figure 18. SEEKERe colorimeter by Detectachem [95]

The manufacturer states a waterproof rating of IP66, which means full hermetic sealing against the ingress of strong water jets. Shock resistance is ensured by a structural design which meets [1].

Table 8. Technical specifications of the DetectaChem SEEKERe portable colorimeter

Manufacturer/ Designation	Substances detected	State of sample aggregation	Detection limit	Device weight [kg]	Ref.
DetectaChem/ SEEKERe	Explosives; Narcotic substances	Liquid; Solid	ng; µg	0.197	[95]

10. Coupled RS and FTIR

Thermo Fisher has developed the unique Gemini mobile detector, which allows processing with two complementary analytical techniques, namely RS and FTIR, to test specimens with a single instrument. The Gemini features a Raman probe on a flexible neck enabling testing to be performed in hard-to-reach areas without moving the sample. The Gemini' design conforms to [1] and, like the TruDefender FTX FEMD, it can be decontaminated by immersing the instrument in a reprocessing liquid. The low weight of this FEMD ensures easy analysis in a potentially contaminated area. The manufacturer claims high sensitivity of the touchscreen for gloved operation and, as an option, there is a simplified keyboard control. The Gemini software has two add-ons (as of the year 2024). The LowDoseID software, which, together with SERS analysis accessories, enables increased detection RS sensitivity. The HazmasterG3 add-on significantly extends the identification of hazardous substances, enabling assessment of hazard scenarios. In practice, the software, based on the available information about chemicals in the case of detection and identification of several compounds, can simulate the possible applications of the substance with an estimation of the amount of the final product. This simulation enables the operator to assess the potential risks and decide on how to proceed. The add-on has been developed primarily for chemical and unexploded ordnance emergency responders.

Table 9. Performance of the Thermo Fisher Gemini FEMD

Manufacturer/ Designation	Substances detected	State of sample aggregation	Infrared range [cm^{-1}]/ resolution [cm^{-1}]	Device weight [kg]	Ref.
Thermo Fisher Scientific, Inc./ Gemini	Explosives; CWs; TICs/TIMs; Narcotic substances	Liquid/solid	FTIR: 4000-650/ 4	1.81	[96]
			Raman: 2875-250/ 7-10.5		

11. Coupled IMS and electrochemical sensors

Detectors utilising more than one analytical technique not only enable a wider range of hazardous substances to be analysed, but also increase the reliability of the results. A unique solution is provided by Airsense Analytics; the GDP-X explosive material detector (Figure 19).

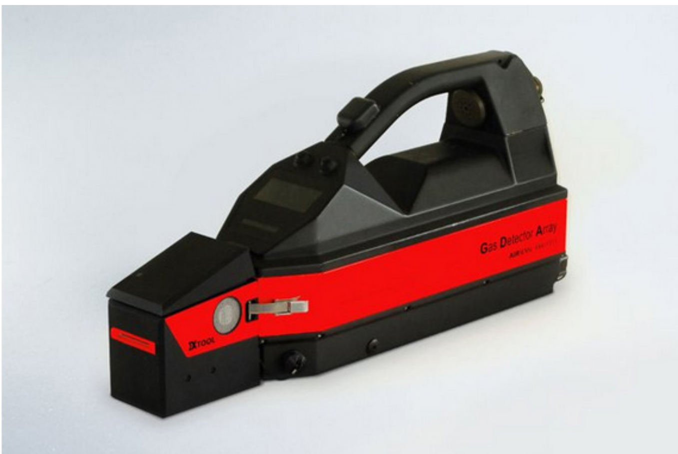


Figure 19. GDP-X explosive material detector by Airsense Analytics [97]

The GDA-X has an advanced operating mode designed for the analysis of substances with low vapour pressures, which characterises most explosives. For this purpose, an X-TOOL adapter attached to the front of the instrument is used, in which the analysed substance is desorbed. The manufacturer declares that a Geiger-Muller sensor can be added, increasing the operational range of the device to include response to gamma and X-rays.
Another example of IMS applications combined with several solid-state sensors is the ChemProX detector from Bertin Environics of Finland, built in compliance with [1] (Figure 20, Table 10). The ChemProX features an assigned pump continuously monitoring the environment. The manufacturer states that up to 10 devices can be clustered together for deployment in the given area to be monitored.

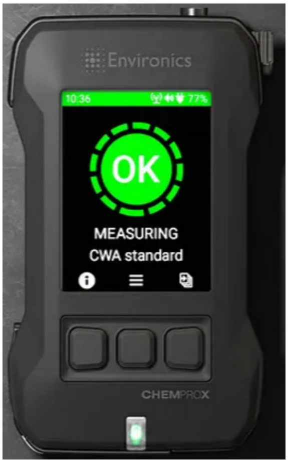


Figure 20. ChemProX detector by Bertin Environics [98]

Table 10. Performance of coupled IMS electrochemical sensor detectors

Manufacturer/ Designation	Substances detected	State of sample aggregation	Detection limits	Device weight [kg]	Ref.
Airsense Analytics/ GDA-X	RDX, PETN, TNT, NG, EGDN, HMTD, TATP; Gamma radiation, X radation	Aerosol/gas	ppt, ppb, ppm, ng	4.2	[97]
Bertin Environics/ ChemProX	Explosives; CWs; TICs/TIMs; Narcotic substances; Other		ppm	0.73	[98]

12. Development prospects

Following a review of the literature and the portfolio of leading instrument manufacturers and suppliers, 73 detectors utilising five different analytical techniques were catalogued with a group of representative colour test kits being included. One of the most important indicators of the development potential of a technique/ device is the number of models from different manufacturers. The technique with a high development potential is undoubtedly IMS. The technique ranked second in this regard is Raman spectroscopy (RS). IMS and RS have the clear advantage of enabling analysis without direct contact with the sample.
The second important path of development for field explosion material detectors is an application of coupled techniques. Flagship examples are the Gemini (Thermo-Fisher), the GDA-X (Airsense) and the Griffin 510 (FLIR).
A third path of development is the use of new techniques which have not yet been commercialised; an example of this is the attempt to combine sample heating with linear temperature ramping and real-time

analysis of the gases emitted from the test sample, which is called TE-FTIR (thermaly enhanced Fourier transform infra-red) spectrometry [99]. Another example is the development of electrodes which are selective towards specific hazardous compounds, used in voltammetry [100].

Further development of FEMDs includes the use analytical techniques not previously considered for portable or field applications. An excellent example is the series of QMB devices from MS Technologies. Although the QMB technique has been known for many years, it is only recently that an attempt has been made to use it in FEMDs.

In an attempt to predict the most important development trends, it is expected that manufacturers will continue to strive for miniaturisation of equipment, integration of multiple analytical techniques in a single detector and - something already becoming apparent - reduction of operator activities to a bare minimum during the test or analysis process.

13. Conclusions

Based on the analysis of the material collected, the following conclusions can be made:

- Detector specifications provided by manufacturers in open sources do not always make it clear which chemicals are detected and basic information such as analysis time or detection limit is often missing.
- Recent years have led to a rapid increase in the number of commercially available mobile detectors. This is linked to the observed increase in the activity of criminal and terrorist organisations.
- Leading manufacturers of mobile detection equipment provide design solutions which enable operations even in extreme conditions with post-operational decontamination of the entire device made feasible.
- Current solutions minimise the operator's involvement in the analysis process and sometimes reduce it to powering on the detector and reading the result obtained. This eliminates the impact of random factors on the reliability of analysis.
- Selected detectors feature systems for automatic cleaning and returning to operational readiness after detection of a hazardous substance.
- Advances in precision mechanics and microelectronics have allowed the construction of multi-sensor devices and integration of two (or more) analytical techniques within a single device.
- The mobile detectors with the best operational capabilities are those developed by major corporations which have specialised in the design of analytical equipment for decades and very often work closely with the military and law enforcement services.

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