

Romolo, F.S.; Connell, S.; Ferrari, C.; Suarez, G.; Sauvain, J.J.; Hopf, N.B.  
**Locating bomb factories by detecting hydrogen peroxide.** *Talanta* 160:  
15-20, 2016.

Postprint version	Final draft post-refereeing
Journal website	<a href="http://www.sciencedirect.com/science/journal/00399140">http://www.sciencedirect.com/science/journal/00399140</a>
Pubmed link	<a href="http://www.ncbi.nlm.nih.gov/pubmed/27591582">http://www.ncbi.nlm.nih.gov/pubmed/27591582</a>
DOI	<a href="https://doi.org/10.1016/j.talanta.2016.06.033">10.1016/j.talanta.2016.06.033</a>

## Locating bomb factories by detecting hydrogen peroxide

Francesco Saverio ROMOLO<sup>1,2</sup>, Samantha Connell<sup>1</sup>, Carlotta Ferrari<sup>1</sup>, Guillaume Suarez<sup>3</sup>, Jean-Jacques Sauvain<sup>3</sup>, Nancy B. Hopf<sup>3</sup>

<sup>1</sup>Institut de Police Scientifique (IPS), Université de Lausanne, 1004 Dorigny – Lausanne, Switzerland.

<sup>2</sup>Legal Medicine Section, Department SAIMLAL, SAPIENZA Università di Roma, Viale Regina Elena, 336, Rome, Italy.

<sup>3</sup>Institute for Work and Health (IST), 1066 Epalinges – Lausanne, Switzerland.

### Abstract

The analytical capability to detect hydrogen peroxide vapour can play a key role in localizing a site where a H<sub>2</sub>O<sub>2</sub> based Improvised Explosive (IE) is manufactured. In security activities, it is very important to obtain information in a short time. For this reason, an analytical method to be used in security activity needs portable devices. The authors have developed the first analytical method based on a portable luminometer, specifically designed and validated to locate IE manufacturing sites using quantitative on-site vapour analysis for H<sub>2</sub>O<sub>2</sub>. The method was tested both indoor and outdoor. The results demonstrate that the detection of H<sub>2</sub>O<sub>2</sub> vapours could allow police forces to locate the site, while terrorists are preparing an attack. The collected data are also very important to develop new sensors; able to give an early alarm if located at a proper distance from a site where an H<sub>2</sub>O<sub>2</sub> based IE is prepared.

Keywords: Precursor, Improvised Explosive (IE), Improvised Explosive Devices (IED), Home Made Explosive (HME), security, hydrogen peroxide, luminol,

### Introduction

The study of precursors used to produce explosives, is a forensic field of increasing importance. These precursors allowed home-made preparations of improvised explosives (IE) used in several recent bombings [1-4], possibly including the recent terrorist attacks in Paris [5]. The European Parliament and the Council adopted the Regulation (EU) No. 98/2013 on the marketing and use of explosives precursors on 15 January 2014 [6]. According to this regulation, seven precursors shall not be available to the general public anymore in

concentrations greater than their limit values listed in Table 1. Despite the importance of the subject, few articles can be found in the scientific literature when searching with the keywords “explosive” and “precursor”.

	ANNEX I Regulated Substance	Limit Value (w/w)
1	Hydrogen Peroxide	12%
2	Nitromethane	30%
3	Nitric acid	3%
4	Potassium Chlorate	40%
5	Potassium Perchlorate	40%
6	Sodium Chlorate	40%
7	Sodium Perchlorate	40%

Table 1. Substances available to the public at concentrations equal or lower than the limit value according to Regulation (EU) No. 98/2013 of the European Parliament and of the Council on the marketing and use of explosives precursors (Annex 1) [6].

Chung et al. developed a methodology to prioritise potential precursor chemicals in order to assess the urgency of controls based on commodity chemicals being controlled under Korean regulations [7]. Considering analytical papers, standoff deep Raman allowed remote detection of concealed explosive precursors such as nitromethane and ammonium nitrate [8]. Ali et al. detected ammonium nitrate, hexamethylenetetraamine and pentaerythritol on clothing by Raman microscopy, after spotting particles with optical microscopy [9]. Nazarian and Presser used a laser-driven thermal reactor to obtain the thermal/chemical signatures of nitromethane and ammonium nitrate [10]. Finally Lazarowski and Dorman studied the capability of trained detection dogs to correctly signal the presence of one or more explosive mixtures containing potassium chlorate [11]. In addition, some authors have evaluated an isotopic analysis application to study a possible association between precursors used as starting material and explosive products obtained [12-15].

The scientific literature search was later focused on hydrogen peroxide ( $H_2O_2$ ). This explosive precursor is of particular importance after its involvement in the foiled plot to blow up several aircrafts during their flights from London-Heathrow Airport. In this case,  $H_2O_2$  was used to prepare homemade liquid explosives [16]. This kind of explosive, capable of detonating [17], was extensively studied in UK during the investigation and the criminal trial [18, 19]. Hydrogen peroxide (aq) has been detected through containers or packaging using Raman spectroscopy

[20, 21]. Ramirez-Cedeno et al. reported analyses of  $\text{H}_2\text{O}_2$  concealed in mixtures with alcoholic beverages, such as whiskey, rum, and tequila via Raman [22]. Petterson et al. demonstrated the standoff detection capability of Raman with 5%  $\text{H}_2\text{O}_2$  solutions in water through coloured glasses and PET at 30 m [23]. Stewart et al. proposed a handheld Raman spectrometer to determine  $\text{H}_2\text{O}_2$  concentrations in liquids found at suspected IE manufacturing sites [24].

An online analyser was developed and used by Francois et al. in the field to measure atmospheric  $\text{H}_2\text{O}_2$  obtaining values down to  $3.5 \times 10^{-1} \mu\text{g m}^{-3}$  (177 pptv) [25]. Cotton swabs used for sample collection of hydrogen peroxide post-blast have been analysed using reversed-phase high-performance liquid chromatography with either fluorescence detection (HPLC–FD) or electrochemical detection (HPLC–ECD) [26, 27].

With the new  $\text{H}_2\text{O}_2$  limit concentration for the products available to the general population (12%), criminals intending to use  $\text{H}_2\text{O}_2$  to produce IE are forced to carry out a concentration process, as was done in 2005 in a flat in New Southgate, London. Terrorists allegedly used 443 litres of a commercial product containing hydrogen peroxide (18% concentration), and to have concentrated the  $\text{H}_2\text{O}_2$  in heated pans in the kitchen to prepare the IE. Heating such liquids is expected to disperse significant  $\text{H}_2\text{O}_2$  vapours into the surrounding air continuously throughout the production phase of the IE [28]. The detection of such vapours could allow police forces to locate sites, where the on-going manufacturing of a  $\text{H}_2\text{O}_2$  based IE is suspected. This approach for protecting citizens from bombings is expected to be more effective than simply patrolling a possible target, because the production time of IE is much longer than the time needed to transport an improvised explosive device (IED) close to the target from the manufacturing site [29]. To our knowledge, no method has been specifically designed and validated to locate IE manufacturing sites using quantitative on-site vapour analysis for  $\text{H}_2\text{O}_2$ . The aims of the research described in this paper were to develop a sampling and on-site detection method allowing low levels of  $\text{H}_2\text{O}_2$  vapour to be measured for security reasons. This method was further tested at a military test site, where  $\text{H}_2\text{O}_2$  vapours were emitted from a bomb factory kitchen.

## Materials and Methods

## Safety note

A literature and media review was completed to become familiar with the typical procedures used to concentrate commercially available  $\text{H}_2\text{O}_2$ , which is a dangerous material. The handling of this substance in general and the activity described in this article in particular may only be carried out by authorised and highly qualified personnel, using appropriate safety measures (reinforced goggles and gloves, splinter-proof vessels, protective shield, etc.). Moreover, in Italy “It is forbidden to manufacture, to hold at home or elsewhere, to transport or to sell ... explosives that have not been recognised and classified by the Minister of the Interior” [30], such as mixture containing  $\text{H}_2\text{O}_2$ .

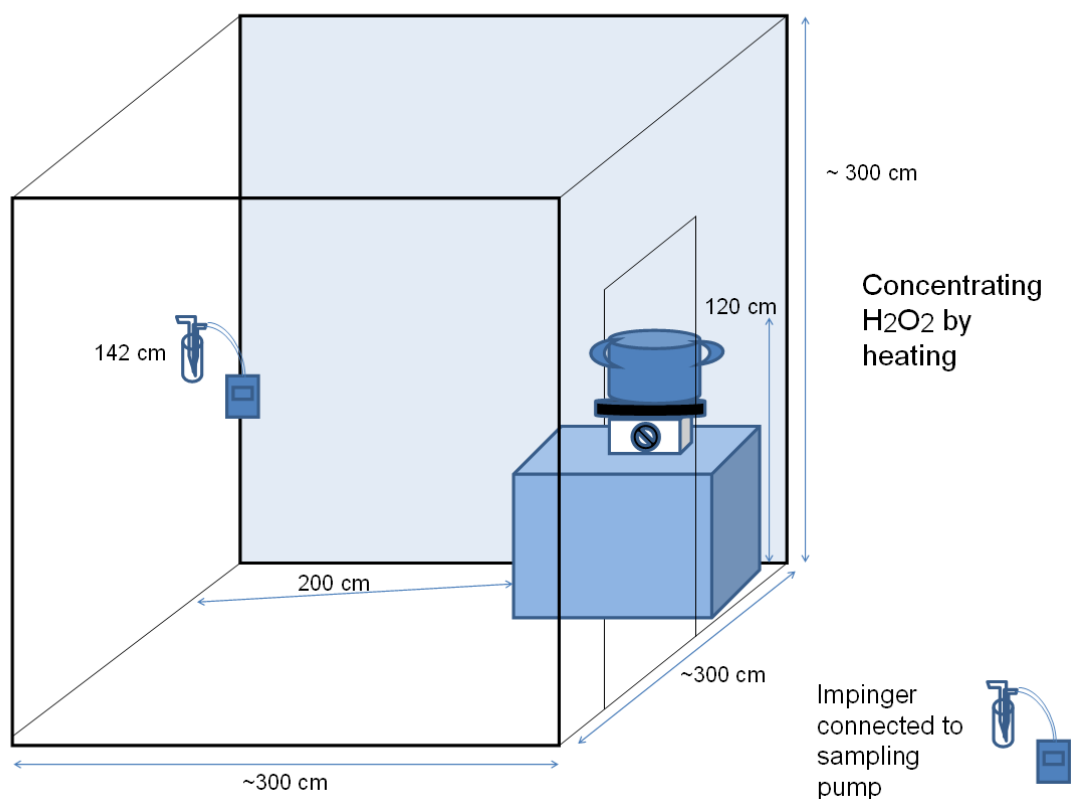
## Materials

Hydrogen peroxide (12%) was purchased from a general store and  $\text{H}_2\text{O}_2$  (30%) from Sigma Aldrich (5L, ref. 16911-5L-F, St. Louis, MO, USA). A 12 L stainless steel casserole (24 cm diameter) was also bought from a general store. A hot plate with a magnetic stirrer (Bibby, HC1202), a glass laboratory thermometer, and an oscillating fan operating statically (Sanyo) were used. A weather station was used to determine wind direction in field experiments (IROX model PRO-X2, ref. #IR4.1769.30).

## Approach

To estimate  $\text{H}_2\text{O}_2$  vapour emissions during concentration steps via heating, two approaches were used; a controlled laboratory experiment and a mock test. Three tests were performed in a controlled environment [31] at the Institute for Work and Health (IST) (Lausanne, Switzerland). Hydrogen peroxide sampling at different distances from the source were carried out inside a closed and ventilated exposure chamber ( $10 \text{ m}^3$ ) (Figure 1). The capability of the developed method to detect  $\text{H}_2\text{O}_2$  vapours in field conditions was tested at the Armasuisse, Science & Technology Competence Center in Thun, Switzerland, where an IE manufacturing site was created and used as a model. The drawing in Figure S1 of the supplementary material section shows the experimental set-up on-site with the positions of the IE manufacturing site and the sampling units located along the direction of the wind.

Figure 1. Drawing depicting exposure chamber experimental set-up at IST.



### Air sampling

Air samples were collected using a personal air sampling pump (SKC AirChek 500 or SKC AirChek 224 PCXR4; Eighty Four, PA, USA), connector tubing (Tygon<sup>®</sup>), and glass impingers (SKC Fritted Midget Impinger, Glass, 25 mL, with Standard Nozzle) containing water (15 mL from Milli-Q Q-POD, Switzerland, 18.2 M $\Omega$ .cm, < 4 ng/g total organic carbon, filtrated through 0.22  $\mu$ m filter) operated at a flow rate of 1 litre per minute (Lpm) (Figure 2).

Figure 2. Photo of sampling train used to sample  $H_2O_2$ , attached to poles at increasing distances, as shown in Figure S1 of the supplementary material section.



## Chemiluminescent Method Development

### *Bench-top analysis*

Chemiluminescence methods were sensitive to  $\text{H}_2\text{O}_2$  and appeared convenient for the envisioned application. The method described here corresponds to the combination of two published chemiluminescent (CL) methods for  $\text{H}_2\text{O}_2$  [32], [33], and one for peroxide-based

explosives [34]. A horseradish peroxidase (HRP) and luminol mixture was used to react with  $H_2O_2$  and produce a light emission, which was analysed by a luminometer, providing quantitative results. Preliminary tests to determine sensitivity of two types of HRP in buffer solutions (VI in PBS and X in Tris) were carried out.

- HRP type VI (from horseradish, Sigma Aldrich, Switzerland, N° P8375-1KU) in Phosphate buffer (PBS), pH 7.4 (Bichsel AG, Interlaken Switzerland) or in 0.1 M Tris buffer (pH 8.4)
- HRP type X (from horseradish, ammonium sulphate suspension, Sigma Aldrich, Switzerland, N° P6140-2KU) in 0.1 M Tris buffer (pH 8.4)

The optimised reaction mixture for the bench-top luminometer consisted of mixing luminol (5 mL, 10 mM in 0.1 M Tris buffer pH 8.4) and HRP type X (10 mL, 5 U/mL in 0.1M Tris buffer pH 8.4). A microplate reader in CL mode (Tecan Infinite M200, Männedorf, Switzerland) was used to quantify the  $H_2O_2$  concentrations. The microplate reader results were considered the reference value. Samples (standard  $H_2O_2$  solution (250  $\mu$ L, 0-3  $\mu$ M) or sample (250  $\mu$ L)) were introduced in defined wells in a white 96 well microplates (Nunclon Delta N° 136101).

The optimised HRP/luminol mixture (10  $\mu$ L) was then injected in the well, followed by measurement of the luminescence intensity every 20 seconds during a total time of 15 minutes (45 cycles). The integration of the emitted light over time was related to the  $H_2O_2$  concentration in the sample. The calibration curve fitted a second order polynomial function forced to zero, consistent with literature data [32].

#### *On-site analysis by portable luminometer*

For on-site measurement,  $H_2O_2$  concentrations were measured using a portable luminometer (Hygienia EnSURE, Camarillo, CA, USA). As this instrument is fully manual, it is not possible to record the light emission immediately after addition of the HRP/luminol mix. Some delay (allowing for shaking and introducing the sample in the instrument) was needed before measurement started. Preliminary tests were performed to optimise the light emission by modifying the HRP/luminol ratio. Four HRP/luminol mix (ratio 5/2.5; 2.5/5; 1.25/6.25; 0.625/6.375 volume:volume) of HRP Type X 5 U/mL and luminol 10 mM in Tris buffer (pH 8.4) were prepared and tested and the final optimised concentrations of the HRP/luminol mixture used with the portable luminometer corresponded to mixing 1.25 mL HRP type X 5U/mL in 0.1M Tris buffer pH 8.4 with 6.25 mL luminol 10 mM in 0.1M Tris buffer pH 8.4.



Original Aquasnap tubes (Aquasnap<sup>®</sup> ATP water test, Art. AQ-100X) were modified by cutting the mixing wand to optimize their use in this project. To avoid possible contamination, the tubes were washed with deionized water (three times per tube) and methanol (one time per tube), followed by air drying before use. Hydrogen peroxide standard solutions (0-4  $\mu\text{M}$ ) or impinger samples (500  $\mu\text{L}$ ) were added to a pre-washed tube. The optimised HRP/luminol mix (30  $\mu\text{L}$ ) was added to the sample, the tube shaken manually to ensure well mixing, inserted into the portable luminometer and analysed. Five seconds elapsed from adding the luminol mix to the start of the readings. After 15 seconds, the amount of light emitted (in arbitrary units) was recorded, followed by seven additional light measurements over the next 120 seconds, manually read on the portable luminometer, shown in Figure S2 of the supplementary material section. The sum of these eight measurements corresponded to the total light emitted during two minutes. Each measurement was performed in triplicate. Tubes were washed as above and reused after each experiment.

#### Experimental Set-up

In the experiments performed in the exposure chamber, an initial volume of  $\text{H}_2\text{O}_2$  (aq) was measured in a glass cylinder and poured into a pot on top of an electric hot plate. The initial volume of aqueous  $\text{H}_2\text{O}_2$  to concentrate, varied by experiment, ranging from 2.1 to 3.6 L. The initial  $\text{H}_2\text{O}_2$  (aq) concentration varied by experiment, ranging from 4.5 to 7 M. The heating procedure lasted a minimum of 4 hours and final  $\text{H}_2\text{O}_2$  concentrations could be as high as 24.5 M in the pot. Air samples were collected every 20 minutes, then capped, and stored under refrigeration until analysis. Curves of increasing  $\text{H}_2\text{O}_2$  concentrations in air over time were generated.

The field test simulating  $\text{H}_2\text{O}_2$  concentration in order to understand the environmental concentration profile and the effect of dilution was carried out at Armasuisse, Science & Technology Competence Center in Thun, Switzerland. Four litres of 30%  $\text{H}_2\text{O}_2$  was concentrated for approximately 4.5 hours with the same procedure adopted for the laboratory experiments performed in the exposure chamber. The source was located approximately 0.5 m from the bomb factory window. A total number of 20 air samples were collected. Sampling trains were taped to metal poles at 155 cm height and placed at distances 0.5 – 20 meters from the source in the direction of the wind (Figure 3). Sample times and distances of the

impingers from the source were based on real-time results obtained by the portable luminometer. As positive results were received at close distances with the direct-reading instrument, the stationary samplings were moved further away from the source, and sampling times were increased with distance. Sampling times ranged from 15 – 50 minutes.

Figure 3. Photo of sampling poles located at increasing distances from the source.



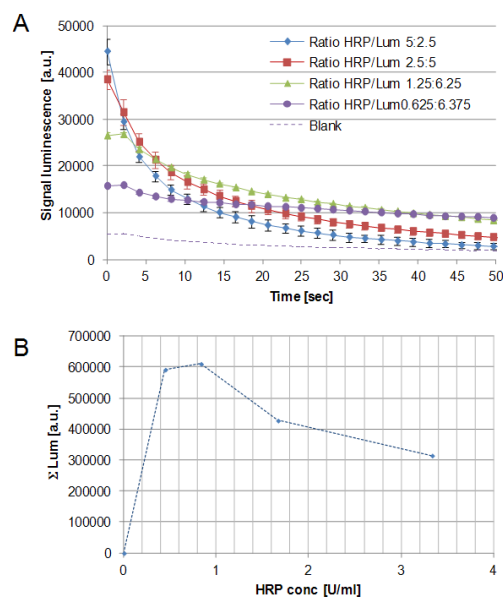
### Results and discussion

Preliminary tests regarding the effect of the HRP type on the chemiluminescence signal were measured using  $\text{H}_2\text{O}_2$  standard solutions. Due to solubility problems for luminol at pH 7.4, tests were performed only at pH 8.4 with 0.1M Tris buffer. Whereas luminescence intensities were always slightly higher for HRP type VI compared to HRP type X, no statistically significant luminescence differences for the  $\text{H}_2\text{O}_2$  concentration above  $1 \mu\text{M}$  were observed between the two HRP mixtures tested (Student t-test,  $p > 0.05$ ). Figure S3 in the supplementary material section shows the calibration curves for  $\text{H}_2\text{O}_2$  standard solution with HRP/luminol mixture either with HRP Type VI (blue curve) or HRP Type X (red curve). Therefore HRP type X was used for all other following chemiluminescence measurements.

The portable luminometer doesn't allow the injection of the reactive HRP/luminol mix directly

inside the measurement cell. Mixing the sample with the HRP/luminol mix must therefore be done before any measurement. This delay means that some of the emitted light was lost. This loss should remain as low as possible in order to be sensitive enough to measure trace levels of  $\text{H}_2\text{O}_2$ . By changing the ratio of the enzyme to luminol, the light emission could be modulated as illustrated in Figure 4. By decreasing the HRP concentration in the mixture, the initial light emission signal clearly decreased but was more constant over time, as illustrated in Figure 4A. The integration values of the emitted light during the first 150 seconds of reaction as a function of the HRP concentration in the reacting media is shown in Figure 4B. The total light emitted was the greatest for a mixture containing about 0.8 U/mL HRP Type X and 8.3 mM luminol in 0.1 M Tris buffer pH 8.4. These conditions (corresponding to 1.25 mL HRP 5U/mL + 6.25 mL luminol 10 mM) were adopted for all the measurements taken with the portable luminometer.

Figure 4 - Testing the ratio of HRP Type X/luminol (volume:volume) on the luminescence kinetic. A): luminescence decay for the different volume ratio; B): Integration of the emitted light during the first 150 seconds of reaction as a function of the HRP concentration in the reacting media. Measurements were done with a standard solution of  $\text{H}_2\text{O}_2$  0.97  $\mu\text{M}$ .

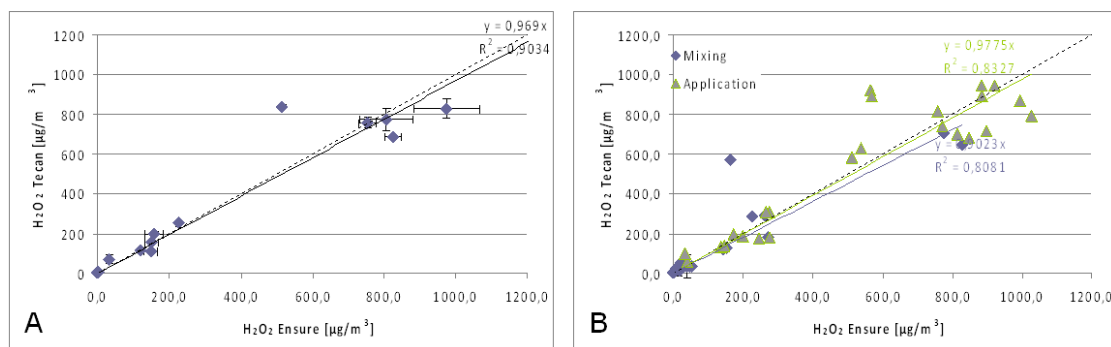


The limit of detection (LOD), corresponding to three times the standard deviation of the signal for a  $\text{H}_2\text{O}_2$  0.1-0.4  $\mu\text{M}$  standard solution, was  $0.1\pm 0.03$   $\mu\text{M}$  with the bench-top luminometer and it was  $0.2\pm 0.03$   $\mu\text{M}$  for the portable luminometer. The LOD for the portable luminometer was also evaluated later, considering a coefficient of variation larger than 30% for duplicate measurement at the LOD. With this approach, a LOD of 0.25  $\mu\text{M}$  was obtained.

When expressed as air concentration, the LOD for the bench plate reader and the portable luminometer translated into 3.4  $\mu\text{g}/\text{m}^3$  and 6.8  $\mu\text{g}/\text{m}^3$  respectively. The precision of the portable luminometer method ( $\text{CV} < 10\%$ ) was 1  $\mu\text{M}$   $\text{H}_2\text{O}_2$  (aq). Calibration curves were obtained over four days, resulting in high repeatability. Figure S4 in the supplementary material section show the high repeatability in  $\text{H}_2\text{O}_2$  calibration using the portable luminometer over four days.

The comparison between the luminescence methods (the microplate bench-top reader and the portable luminometer) gave a very good correlation, obtained by plotting the  $\text{H}_2\text{O}_2$  concentrations in the impinger obtained with both methods (Figure 5). The concordance between the two measurements by using the Bland-Altman plot was good, with a mean of the difference of -6  $\mu\text{g}/\text{m}^3$  (95% confidence limit between +26 and -39  $\mu\text{g}/\text{m}^3$ ). Figure S5 in the supplementary material section shows the Bland-Altman plot demonstrating concordance between  $\text{H}_2\text{O}_2$  levels using the bench-top instrument and portable luminometer.

Figure 5 - Relationship between the  $\text{H}_2\text{O}_2$  results obtained with the bench-top instrument (Tecan) and the portable luminometer (EnSURE). Picture A corresponds to an « averaged » concentration over 15 minutes. Figure B corresponds to two steps: one in blue, averaged concentration over 5 minutes sampling ; and another in green, averaged concentration over 10 minutes sampling.

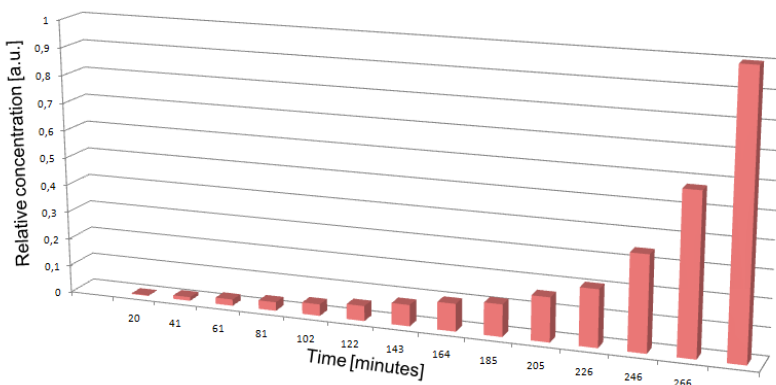


← / ≡ →

### Test Results

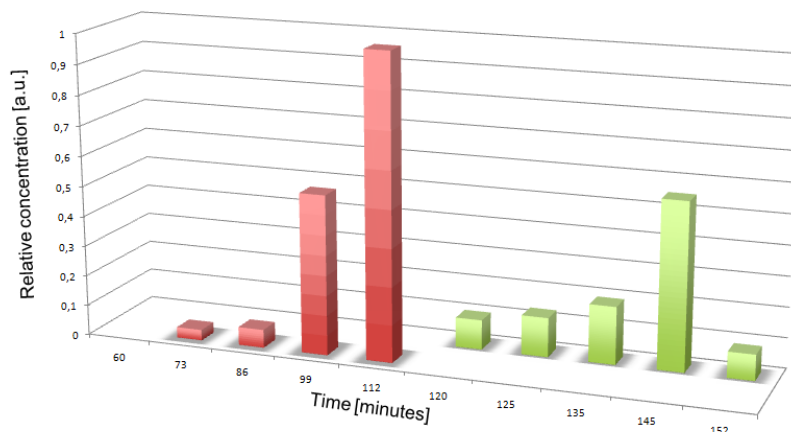
During the three exposure chamber experiments, the initial H<sub>2</sub>O<sub>2</sub> aqueous solutions concentrated in the pot ranged from 5 to 12% and final concentrations ranged from 64 to 84% at the end of the experiments. Fifty-eight air samples were collected during these experiments. The sampling time was always 20 minutes. An example of the evolution of the H<sub>2</sub>O<sub>2</sub> concentration (in arbitrary units) over time indoor is shown in Figure 6.

Figure 6 –H<sub>2</sub>O<sub>2</sub> concentrations in air over time (x axis; in minutes) measured using an impinger. The concentration is reported in arbitrary units normalised to the highest concentration obtained in an indoor test (i.e. the maximum y value is 1 in arbitrary units).



The proposed method was further tested at a military test site, where  $\text{H}_2\text{O}_2$  vapours were emitted from a bomb factory kitchen. Twenty air samples were collected during this test. In both cases the concentration data obtained are confidential EU. For this reason they are reported in Figure 6 and in Figure 7 in arbitrary units normalised to the highest concentration obtained. Despite the understandable limit of confidentiality, we describe here a whole method of making tests, of sampling and of obtaining on-site quantitative data, needed to develop new sensors able to give an early alarm if located at a proper distance from a site where an  $\text{H}_2\text{O}_2$  based IE is being prepared.

Figure 7 –  $\text{H}_2\text{O}_2$  concentrations over time (x axis; minutes) in two impingers, positioned at distance a (in red) and distance b (in green) from the source, with  $b > a$ . The concentration is reported in arbitrary units normalised to the highest concentration obtained in the outdoor test (i.e. the maximum y value is 1 in arbitrary units).



The concentration experiments demonstrated that when hydrogen peroxide is concentrated by heating, a significant amount of hydrogen peroxide in vapour phase is released from the pot into the surrounding air, both indoor and outdoor.. As expected, concentrations generated in the chamber were greater due to the confined (non-diluted) area compared to the field results. Air sampling is highly affected by environmental conditions, especially by the wind direction and speed, resulting in extensive dilution of the contaminant in the environment. Despite outdoor dilution, the results obtained showed that it is possible to detect  $H_2O_2$  vapours using the proposed on-site analytical approach, allowing possible detection during the manufacturing of an  $H_2O_2$  based IE. The detection of such vapours could allow police forces to locate the site, where terrorists are preparing an attack, during the long time needed to prepare the charge. The collected data can also be used to estimate  $H_2O_2$  concentrations that could be found at some distance from the source, in the case of an artisanal bomb factory.

## Conclusion

After the adoption of the European Parliament and the Council Regulation (EU) No. 98/2013 on the marketing and use of explosives precursors in January 2014, there is a new interest about on-site precursor detection for security purposes. We have focused the attention on hydrogen peroxide, which is a building block involved in several terrorist attacks in recent

history. Our developed approach targets the time the terrorists need to concentrate  $H_2O_2$  when  $H_2O_2$  vapours can be measured in air. We have developed for the first time an analytical method specifically designed to provide quantitative on-site analysis for airborne  $H_2O_2$ . The method, based on a portable luminometer, was validated and tested both indoors and outdoors. In the latter case,  $H_2O_2$  vapours were emitted from a bomb factory kitchen on a military base.

The analytical procedure proposed is not only a considerable tool to protect the security of citizens by terrorist attacks and to support the activities of Police Forces; but it is also very important to support the development of new sensors, aiming to locate Improvised Explosive (IE) manufacturing sites. an early alarm of the related threat.

#### Aknowledgments

The project BONAS was funded under the 7<sup>th</sup> Framework Programme of the European Commission, grant agreement no. 261685. The authors would like to thank Loic Blum for his fruitful suggestions and Patrick Folly for his support during the tests in the Armasuisse site in Thun (Switzerland).

#### References

- [1] M. Marshall, J.C. Oxley, Eds. Aspects of Explosives Detection, Elsevier, 2009, page 21.
- [2] Department of Justice, Office of Public Affairs, Umar Farouk Abdulmutallab Sentenced to Life in Prison for Attempted Bombing of Flight 253 on Christmas Day 2009, Thursday, February 16, 2012, <http://www.justice.gov/opa/pr/2012/February/12-ag-227.html> (last accessed 16<sup>th</sup> February 2016).
- [3] Transportation Security Administration, UK 2006 Liquid Explosives Plot Trial Overview, <http://www.tsa.gov/press/releases/2008/09/08/uk-2006-liquid-explosives-plot-trial-overview> (last accessed 16<sup>th</sup> February 2016).
- [4] Intelligence and Security Committee Report into the London Terrorist Attacks on 7 July 2005, [www.fas.org/irp/world/uk/isc\\_7july\\_report.pdf](http://www.fas.org/irp/world/uk/isc_7july_report.pdf) (last accessed 16<sup>th</sup> February 2016).
- [5] <http://www.lefigaro.fr/actualite-france/2015/11/14/01016-20151114ARTFIG00129-attentats-de-paris-un-des-tireurs-identifie.php> (last accessed 16<sup>th</sup> February 2016).
- [6] Regulation (EU) No. 98/2013 of the European Parliament and of the Council on the marketing and use of explosives precursors was adopted on 15 January 2013, [http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L\\_.2013.039.01.0001.01.ENG](http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2013.039.01.0001.01.ENG) (last accessed 16<sup>th</sup> February 2016).
- [7] S.T. Chung, Y.Yoon, H.J. Park, Journal of Loss Prevention in the Process Industries 26 (2013) 1679-1684.
- [8] E.L. Izake, B. Cletus, W. Olds, S. Sundarajoo, P.M. Fredericks, E. Jaatinen, Talanta 103 (2013) 20-27.



- [9] E.M.A. Ali, H.G.M. Edwards, I.J. Scowen, *Journal Raman Spectroscopy* 40 (2009) 2009-2014.
- [10] A. Nazarian, C. Presser, *Thermochimica Acta* 576 (2014) 60-70.
- [11] L. Lazarowski, D.C. Dorman, *Applied Animal Behaviour Science* 151 (2014) 84-93.
- [12] C.M. Lock, W. Meier-Augenstein, *Forensic Science International* 179 (2008) 157-162.
- [13] R. Aranda, L.A. Stern, M.E. Dietz, M.C. McCormick, J.A. Barrow, R.F. Mothershead, *Forensic Science International* 206 (2011) 143-149.
- [14] C. Lock, H. Brust, M. van Breukelent, J. Dalmolen, M. Koeberg, D.A. Stoke, *Anal. Chem.* 84 (2012) 4984-4992.
- [15] J.D. Howa, M.J. Lott, J.R. Ehleringer, *Forensic Science International* 244, (2014) 152-157.
- [16] International Civil Aviation Organization (ICAO), Working Paper: High-Level Conference on Aviation Security (HLCAS), Montréal, 12 to 14 September 2012. [http://www.icao.int/Meetings/avsecconf/Documents/WP\\_14/LIQUIDS, AEROSOLS AND GELS.en.pdf](http://www.icao.int/Meetings/avsecconf/Documents/WP_14/LIQUIDS, AEROSOLS AND GELS.en.pdf) (last accessed 18<sup>th</sup> November 2015).
- [17] A. Schreck, A. Knorr, K.D. Wehrstedt, P.A. Wandrey, T. Gmeinwieser, J. Steinbach, Investigation of the explosive hazard of mixtures containing hydrogen peroxide and different alcohols. *J. Hazard Mater.* 2004 Apr 30;108(1-2):1-7.
- [18] J.C. Oxley, What's Special About Liquid Explosives? In H. Schubert, Kuznetsov, *Detection of Liquid Explosives and Flammable Agents in Connection with Terrorism*, Springer (2008) 27-38.
- [19] A. Beveridge *Forensic Investigation of Explosions*, Second Edition, CRC (2011) 180.
- [20] C. Eliasson , N. A. Macleod , and P. Matousek, *Analytical Chemistry* 79 (21) (2007) 8185–8189.
- [21] M. Kim, H. Chung, M. Kemper, *J. Pharm. Biomed. Anal.* 48 (2008) 592–597.
- [22] M.L. Ramírez-Cedeño, N. Gaensbauer, H. Félix-Rivera, W. Ortiz-Rivera, L. Pacheco-Londoño, S.P. Hernández-Rivera. *International Journal of Spectroscopy* (2012) 1-7.
- [23] A. Petterson, I. Johansson, S. Wallin, M. Nordberg, H. Ostmark, *Propell. Explos. Pyrotech.* 34 (2009) 297–306.
- [24] S.P. Stewart, S.E.J. Bell, D. McAuley, I. Baird, S.J. Speers, G. Kee, *Forensic Science International* 216 (2012) e5-e8.
- [25] S. Francois, I. Sowka, A. Monod, B. Temime-Roussel, J.M. Laugier, H. Wortham, *Atmospheric Research* 74 (2005) 525–545.
- [26] M. Tarvin, B. McCord , K. Mount, K. Sherlach, M.L. Miller, *J. Chrom. A* 209 (2010) 7564-7572.
- [27] M. Tarvin, B. McCord , M.L. Miller, *Forensic Science International* 209 (2011) 166-172.
- [28] The European Court of Human Rights (Fourth Section), CASE OF IBRAHIM AND OTHERS v. THE UNITED KINGDOM. Applications nos. 50541/08, 50571/08, 50573/08 and 40351/09. <https://lovdata.no/static/EMDN/emd-2008-050541.pdf> (last accessed 18<sup>th</sup>

November 2015).

- [29] H. Önnnerud S. Wallin, H. Östmark, D. Menning, S. Ek, H. Ellis, M. Kölhed, Proc. SPIE 8019, Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense X, 80190Y.
- [30] Testo unico delle leggi di pubblica sicurezza TULPS, Regio decreto 18 giugno 1931, n. 773 in Suppl. ordinario alla Gazz. Uff., 26 giugno, n. 146 – Approvazione del testo unico delle leggi di pubblica sicurezza.
- [31] Guillemin M. Arch. Mal. Prof. 36 (1975) 421-428.
- [32] A. Navas Díaz, F. Garcia Sanchez, J.A. Gonziilez Garcia, Analytica Chimica Acta 327 (1996) 161-165.
- [33] B. Zappacosta, S. Persichilli, F. Mormile, A. Minucci, A. Russo, B. Giardina, P. De Sole, Clinica Chimica Acta 310 (2001) 187–191.
- [34] S. Girotti, E. Ferri, E. Maiolini, L. Bolelli, M. D'Elia, D. Coppe, F.S. Romolo, Anal. Bioanal. Chem. (2011) 400, 313–320.

#### Highlights

- A bomb factory can be located by analysing H<sub>2</sub>O<sub>2</sub> vapours emitted.
- A suitable quantitative on-site vapour analysis for H<sub>2</sub>O<sub>2</sub> is proposed.
- A portable luminometer can effectively support the activities of Police Forces.

Graphical abstract.



Accepted manuscript