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Air Cargo Explosive Screener (ACES) based on the integration of Mobility Analysis and Mass Spectrometry

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EXECUTIVE SUMMARY

- **Company**: SEADM, Morpho and CARTIF created in May 2008 a Joint venture (SEDET), aimed at development of explosive detection equipments,
- **Initial product**: An Air Cargo Explosive Screener (ACES), whose aim is to screen explosive contents in complete trucks, and thereby reduce screening costs to values below $0,01/pound,
- **Technology**: vapor trace detection based on the integration of ElectroSpray Ionization, Mobility Analysis (DMA), and API Tandem Mass Spectrometry,
- **Development stage**: Present equipment is in a transition process from TRL 6 to TRL 7,
- **Present performance**: Sensitivity of 0.1 ppq (parts per quatrillion),
- **Planning:** EU Certification scheduled for 2Q2011

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Present state-of-the-art: Screening size limitations

TSA has determined that: “The maximum size cargo configuration that may be screened is a 48” x 48” x 65” skid”.

Steve Lord declared on June 2010: **“**There is currently no technology approved or qualified by TSA to screen cargo once it is loaded onto a ULD pallet or container—both of which are common means of transporting air cargo on wide-body passenger aircraft.

Prior to May 1, 2010, canine screening was the only screening method, other than physical search, approved by TSA to screen such cargo. However, TSA officials still have some concerns about the effectiveness of the canine teams, and effective May 1, 2010, the agency no longer allows canine teams to be used for primary screening of ULD pallets and containers.”

[1] Statement of Steve Lord, Director Homeland Security and Justice Issues before the Subcommittee on Transportation Security and Infrastructure Protection, Committee on Homeland Security, House of Representatives, June 30th, 2010. **GAO-10-880T.**

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Present state-of-the-art: Cost implications

Screening size limitations imply a heavy cost penalty. As declared by Mr. James Tuttle [1] on July 15, 2008**: "**The cost of technology-based screening is on the order of $0.08-0.12 per pound and is dominated by cargo handling and screening labour".

This very restrictive legislation is due to two technological limitations that everybody knows but rarely anybody mentions (the TSA for security reasons, and industry for obvious commercial reasons). These limitations are the following:

1. An X-Ray operator is unable to detect explosives in amounts below 1 kg when exploring depths higher than 1 m, while the amount of PETN required to crash an aircraft is considerably lower,
2. ETD detectors are unable to detect plastic explosives in the real world, since their sensitivity is on the order of nanograms, and vapors to be found are on the order of picograms (according to our own data).

[1] Mr James Tuttle, Division Head of the Explosives Division, Science and Technology Directorate of the U.S. Department of Homeland Security before the House Committee on Homeland Security, Subcommittee on Transportation Security and Infrastructure Protection, July 15, 2008.http://www.tsa.gov/assets/pdf/non_ssi_acstl.pdf

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User requirements

Main User requirements for an Air Cargo Explosives Screener can be synthesized as follows:

1. Able to screen **ULD pallets, containers and complete trucks up to 110 m^3,**
2. Able to detect substances with a **vapour pressure as low as 10^{-11} atm** (RDX and PETN) in amounts much lower than 1 kg per cargo load,
3. Very high Probability of Detection (PoD),
4. Very low False Alarm Rate (FAR),
5. No Operator “interpretation”, and
6. Cost below $0,01 per pound of screened cargo

Requirements 1 to 3 require a very high sensitivity, while requirement 4 requires a very high resolution. Requirement 5 is automatically met if detection is automatic, and requirement 6 if complete trucks can be screened without unloading them.

Main problem lies in the fact that the physics underlying detection are still partially unknown, so a debate is open over the **sensitivity and resolution levels needed** in order to comply with requirements 1 to 4.

Resolution and sensitivity

Basic detection problem can be stated as follows: the higher the sensitivity level achieved by the detector, the larger the number of new species that appear above the detector threshold, and therefore the higher the discriminating challenge for the detector,

- If the vapor detector is sensitive only to species with a vapor pressure of about 1 atmosphere, it will only detect N_2, so an analyzer is not even necessary. At 10 times this sensitivity it will detect also O_2, and then H_2O, CO_2, Ar, NH_3, etc.
- At a sensitivity level of 1 ppm (10^{-6} atmospheres of vapor pressure), just the human breath, coffee or wine contain over 200 vapor species,
- At a sensitivity level of 1 ppb (10^{-9} atmospheres) there are typically many thousands of volatile species,
- Number of species to be found at 1 ppq (10^{-15}) is unknown. According to our tests, this number could well be higher than 100,000.

Minimum performances required

- According to our own data, explosive vapor detection in the real world requires a sensitivity at least of 0.1 ppq and a resolution above 100,000,
- Such target sensitivity is achievable through state of the art laboratory equipment: 0.1 ppq in 1 m^3 of air is approximately equivalent to 1 pg (picogram), and API mass spectrometers can handle it,
- Such target resolution is achievable as follows :
  - MS provides a resolution around 500 in the mass range of interest [1],
  - MS/MS multiplies this resolution by a factor of 10 [2],
  - DMA offers a resolution gain around 50,
- Minimum detector configured as: Sampler-desorber-ESI-DMA-MS/MS

[1] US Research Council of the National Academies: "Opportunities to improve Airport Passenger Screening with Mass Spectrometry", 2004. See http://www.nap.edu/catalog/10996.html

[2] Martínez-Lozano, P.; Rus, J., Fernández de la Mora; G., Hernández, M.; Fernández de la Mora, J. “Secondary Electrospray Ionization (SESI) of Ambient Vapors for Explosive Detection at Concentrations Below Parts Per Trillion” Journal of the American Society for Mass Spectrometry Volume 20, Issue 2, February 2009, Pages 287-294

What ACES delivers

The ACES system provides the **first high throughput technique capable of explosive detection at a high level of aggregation (ULD pallets, containers and complete trucks), thereby reducing by at least one order of magnitude present cargo screening costs.**

The ACES detector takes advantage of its superior sensitivity and chemical specificity in order to tackle the very demanding task of air cargo explosive screening at a high level of cargo aggregation.

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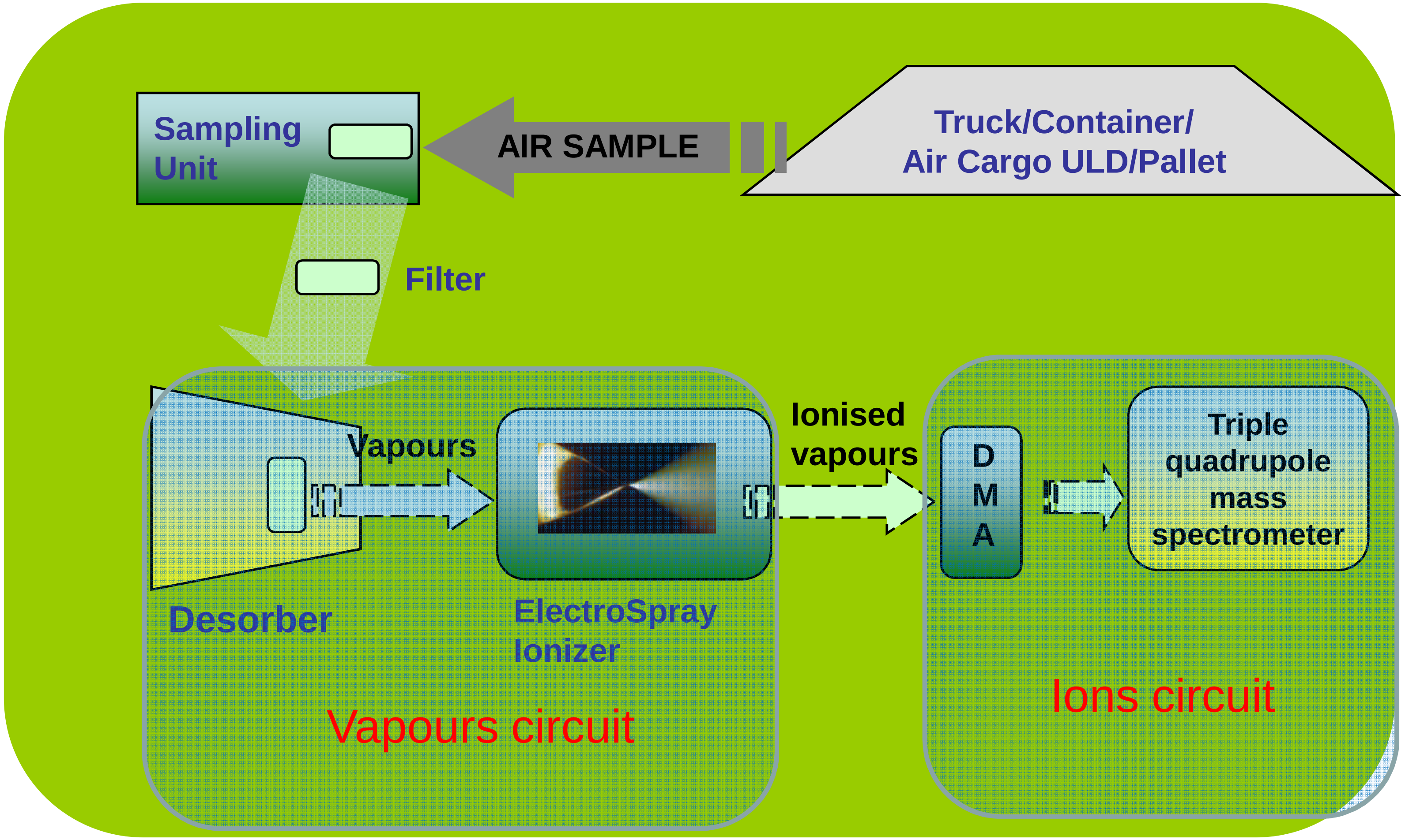
ARCHITECTURE



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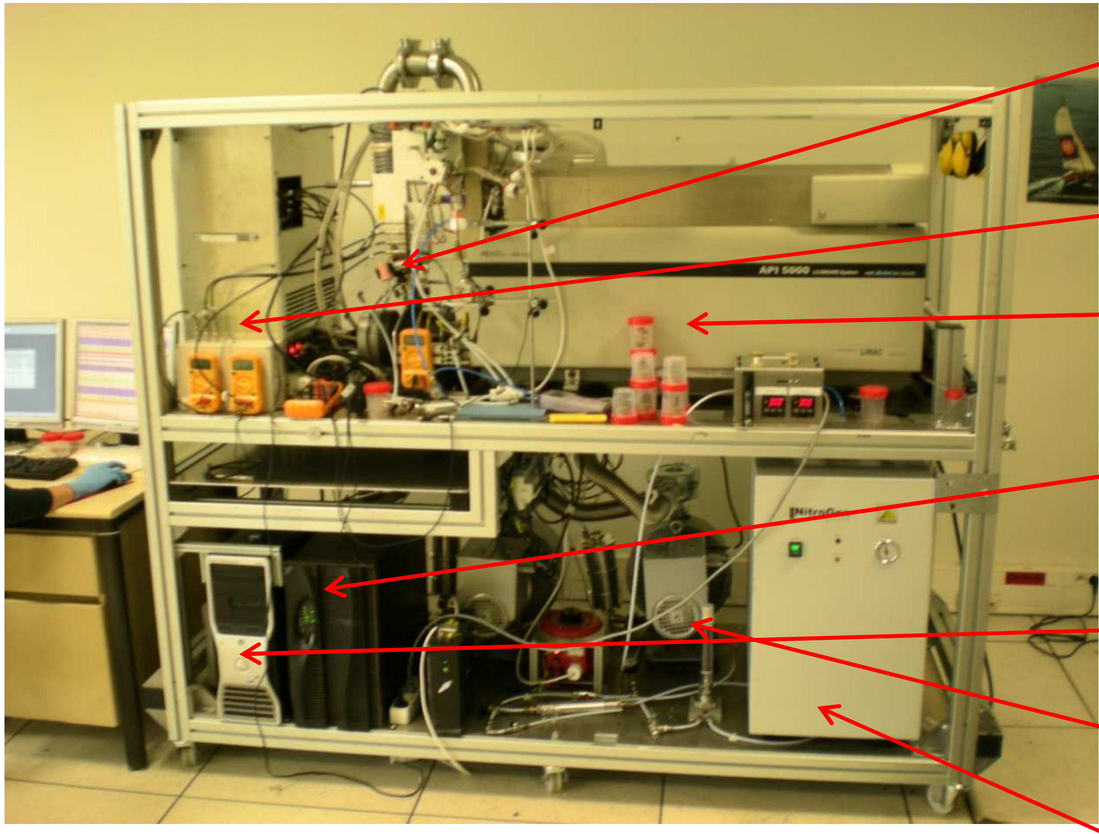
ACES: Analyzer architecture



Desorber- Ionizer-DMA

Electronics

Mass Spectrometer

UPS

Computer

Vacuum pump

N_2 generator

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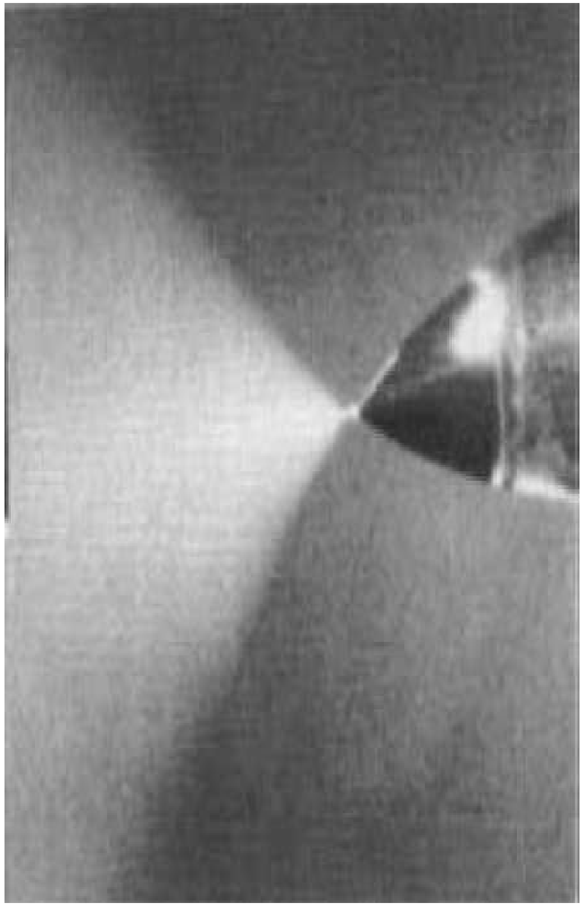
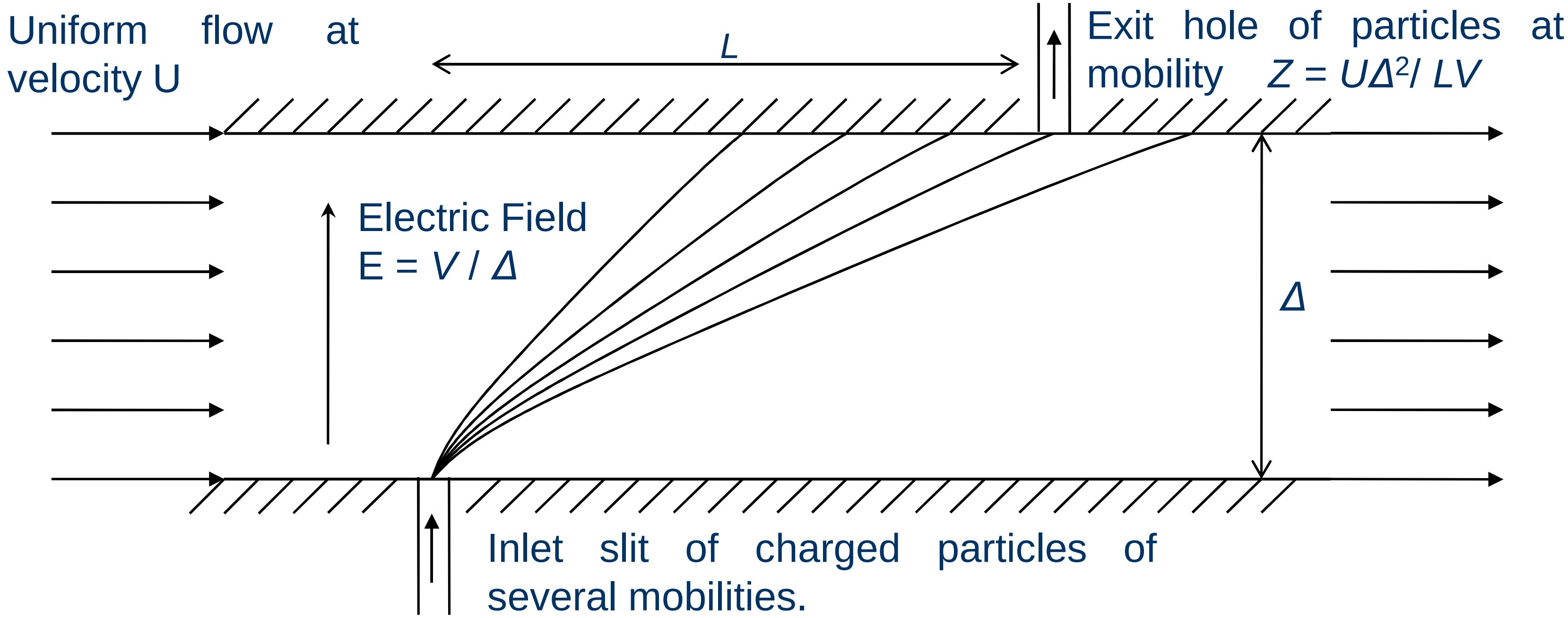
Ionizer: ElectroSpray



- An Electro-Spray (ES) Ionizer is a device originally proposed by Fenn, where a liquid is continuously aerosolised into a fine spray of charged drops. Mixing this spray with an air sample containing vapors (or particles) leads to the ionization of the vapor molecules
- ESI is a "soft" technique, i.e., it does not fragment the molecule it ionizes, thereby allowing the greatest chemical specificity and sensitivity.
- This characteristic is a key component of ACES: other ionization techniques, such as for example corona discharge, are more efficient (i.e., the number of ions generated is higher, even one order of magnitude higher), but they generate a much higher noise level (i.e., ions which are not the molecule sought after), which make them useless for a sensitive detector.

DMA: Sketch



A Differential Mobility Analyzer (DMA) is an instrument that separates ions as a function of their electrical mobility, just as IMS. The main difference between both instruments is that the DMA separates ions in space, while IMS does so in time (inefficient duty cycle). As a result, a DMA has a two orders of magnitude sensitivity gain over an IMS.

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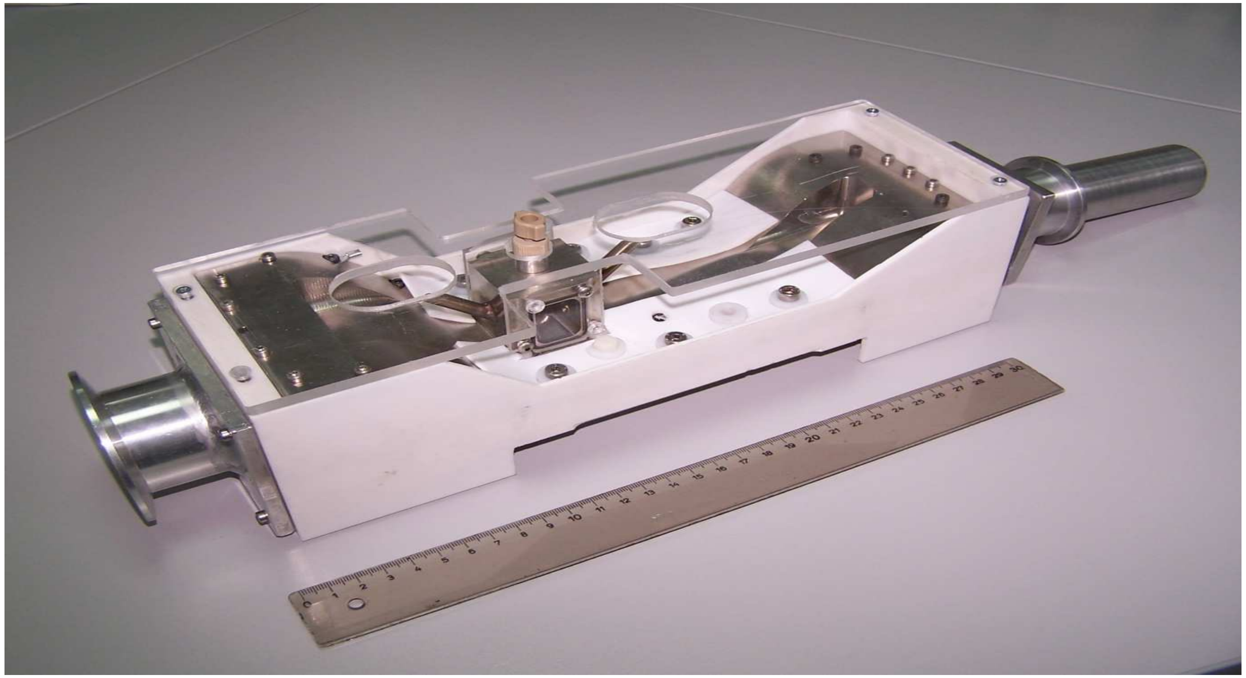
DMA: Picture



Picture of a previous generation flat DMA, where the sheath gas inlet and outlet, and the insulator box (white color) can be seen. The upper part includes the Ionization chamber.

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ACES operation

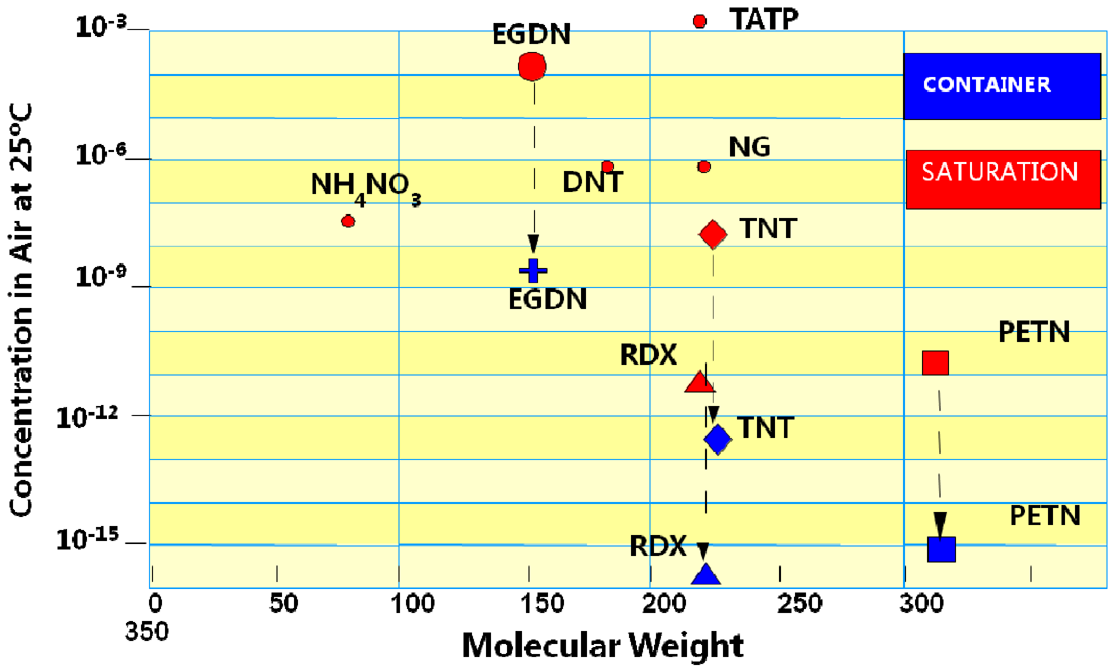
- ACES is based on two units: a Sampler and an Analyzer
- The Sampler is a portable unit with an air pump which extracts air from pallets, containers or truck cargo bays
- The Sampler deposits vapors in a filter, which is brought to the Analyzer
- Analysis can be carried out offline from the sampling operation, at a different location and on a different day

Analyzer operation

Analyzer operation is as follows:

- A filter is inserted in the desorber, where it is heated, and gases generated are driven to the ionization chamber. Currently, a useful signal is maintained between 10 and 20 s,
- The DMA and the MS/MS work synchronously in multiple reaction monitoring mode. Each cycle takes about 1 second,
- Number of counts is calculated for at least two fragment for each explosive, and a positive detection for a specific explosive is launched if:
  - A threshold is reached on most significant fragment of this explosive, AND
  - Fragment ratio for this explosive is within defined limits

Sensitivity



- The attached figure presents, in red colour, the saturation vapour pressure for a few relevant explosives.
- In the real world, vapour pressure is considerably lower than the saturation value. For explosives hidden in cardboard boxes within pallets or containers, our own data points out that real vapour pressure after 15 minutes can be 100,000 times smaller than saturation,
- Sensitivity required in order to detect plastic explosives trough vapour analysis in palletized cargo is as low as 0.1 ppq (10^{-16} atm).

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Test results:

Synthesis

Explosives	Minimal Signal (ppq)	Minimal signal/noise (excluding contamination)
RDX	0.12	TBD
PETN	1.1	TBD
TNT	132	25
EGDN	1.508.000	518

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PERFORMANCE

Present ACES performance is as follows :

- Sensitivity: 0.1 ppq,
- Resolution: has not been reliably measured, theoretical calculations indicate levels around 250,000 (MS = 500; MS/MS gain = 10; DMA gain = 50)
- Sampler throughput: 6 samples per hour,
- Analyzer throughput: 30 tests per hour,
- Probability of detection: 100% for TNT and explosives with higher volatility, TBD for plastic explosives,
- FAR: null for TNT and explosives with higher volatility, TBD for plastic explosives,
- Operational environment: The Sampler has been designed for use outdoors, in a truck parking lot or an aeronautical warehouse. The Analyzer requires a typical office environment, with air conditioning, a temperature range between 15ºC and 25ºC, and humidity below 80%.

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ACES support

- ACES is a complete Program, from R&D to commercialization. It includes three phases:
  - Phase I: R&D (completed on November 30th, 2009),
  - Phase II: Engineering and Certification (planned to end on 2Q2011)
  - Phase III: Pilot tests, Production and Commercialization (planned to begin in 3Q2011)
- ACES is supported by a Spanish Regional Agency (Castilla and Leon ADE), and the Spanish Ministry of Science and Innovation,
- ACES technology is, or has been, supported by the Spanish DoD (DGTECIN), UE FP7 (EFFISEC program) and NATO DAT POW (Defence Against Terrorism Program Of Work)

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Conclusions

- Reliable detection of plastic explosives by trace methods cannot be solved by state-of-the-art techniques, since several orders of magnitude improvements in sensitivity and resolution are required,
- The ESI/DMA/MS/MS technique delivers resolution improvements of 3 orders of magnitude over present state-of-the-art, and allows reliable detection of plastic explosives solely through vapor analysis,
- ACES will be available for operational evaluation in the third quarter of 2011, and might generate a qualitative improvement in operational security procedures for aeronautical cargo,
- ACES offers operational costs considerably lower than present explosive screening equipments (around €0.01/kg).

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Discussion / Questions

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