WASHINGTON STATE UNIVERSITY

Chemical Warfare Agent Simulant Speciation and Detection via Atmospheric Flow Tube-Mass Spectrometry

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Overview

- Trace vapor detection
- CWAs and their simulants
- How does AFT-MS fit in with CWA simulant detection?
- Selected analytes
- Speciation and detection
- Future directions

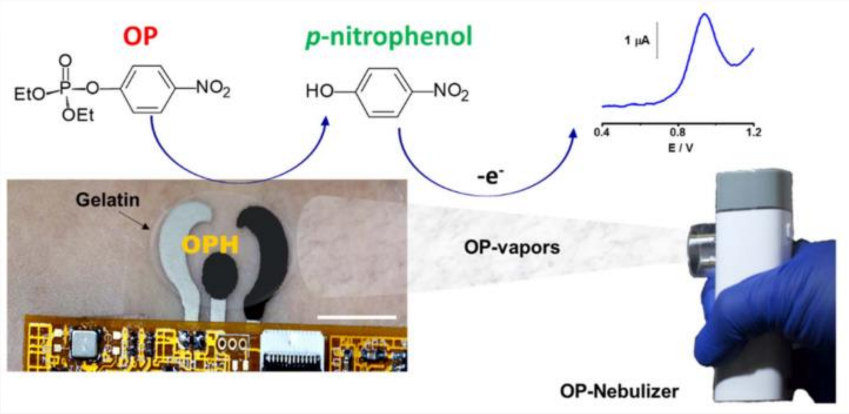
Current Trace Vapor Detection Methods

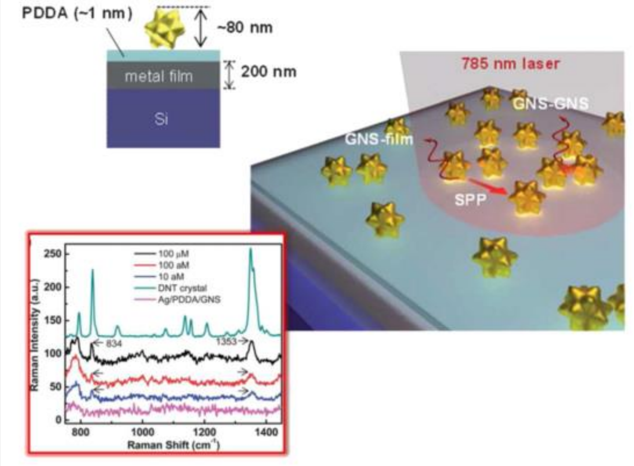
Two general categories of vapor detection techniques:

- Lower selectivity
- Higher selectivity

Current Trace Vapor Detection Methods

- Lower selectivity sensing
  - Sensor polymers or arrays, colorimetric materials
  - Raman spectroscopy
  - Ion mobility spectrometry
- Low barriers to deployment
  - Equipment is portable with simple operation
- Can alert to vapor concentrations of ~1 ppb to >100 ppm





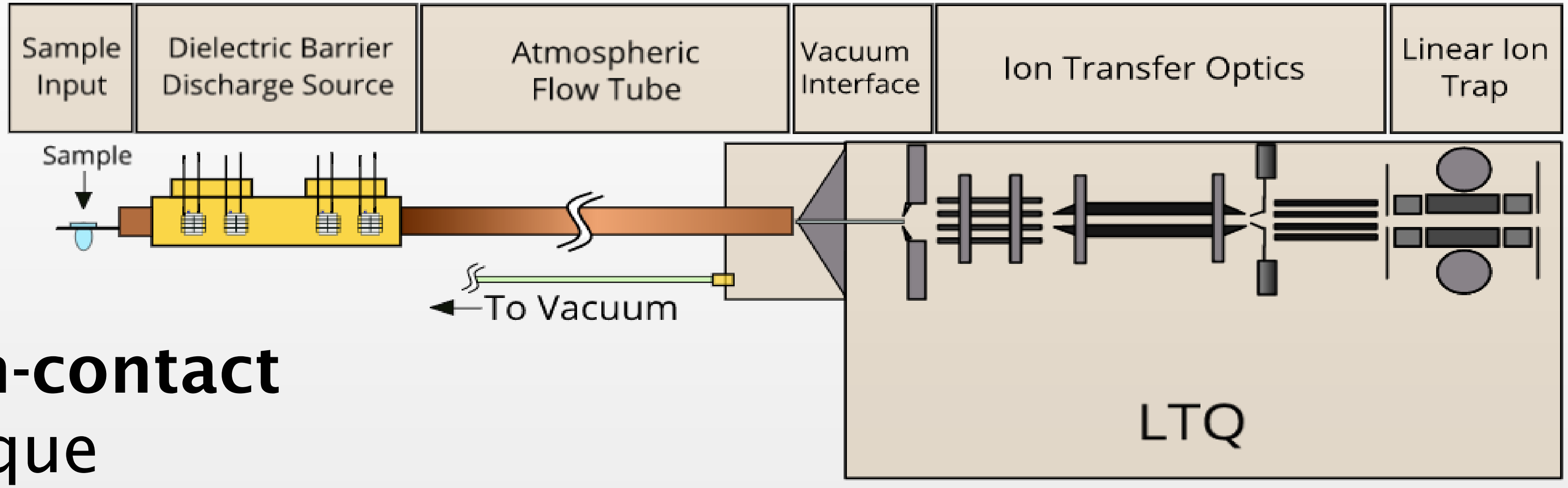
1) Kim et al. *Analytical Chemistry, 88*, **2016**, 9259-9263. 2) Hakonen et al. *Analytica Chimica Acta, 893*, **2015**, 1-13. 3) Wiederoder et al. *ACS Sensors, 2,* **2017**, 1669-1678. 4) Mishra et al. *Biosensors and Bioelectronics*, *101*, **2018**, 227-234.

Current Trace Vapor Detection Methods

- High selectivity detection
  - Sample sorption on solid surface followed by gas chromatography-mass spectrometry
  - **Atmospheric flow tube-mass spectrometry (AFT-MS)**
- Deployment more difficult, but identification more certain
- AFT-MS has demonstrated lowest detection limits of these methods and direct sampling of ambient vapor
  - Can detect low ppt, high ppq analyte concentrations in air

1) Terzic et al. *Journal of Chromatography A, 1225,* **2012**, 182-192. 2) Mäkinen et al. *Analytical Chemistry*, *82,* **2010**, 9594-9600. 3) Ewing et al. *Analytical Chemistry, 85,* **2013**, 389-397.

How Does AFT-MS Fit in with Vapor Detection?



- An open-air, **non-contact** sampling technique
- Reactant ions produced by dielectric barrier discharge source at inlet of tube
- Transit time down tube promotes cluster formation with analyte

1) Ewing et al. *Analytical Chemistry, 85,* **2013**, 389-397. 2) Morrison and Clowers. Characterization of Alkylphosphonic Acid Vapors Using Atmospheric Flow Tube-Ion Trap Mass Spectrometry. *Rapid Comm. Mass Spectrom.*, **2018**. Ahead of print.

How Does AFT-MS Fit in with Vapor Detection?

- Assuming excess of reactant ions, analyte ion quantity can be maximized by increasing *t*
- Simplest way to increase *t* is by using flow tube

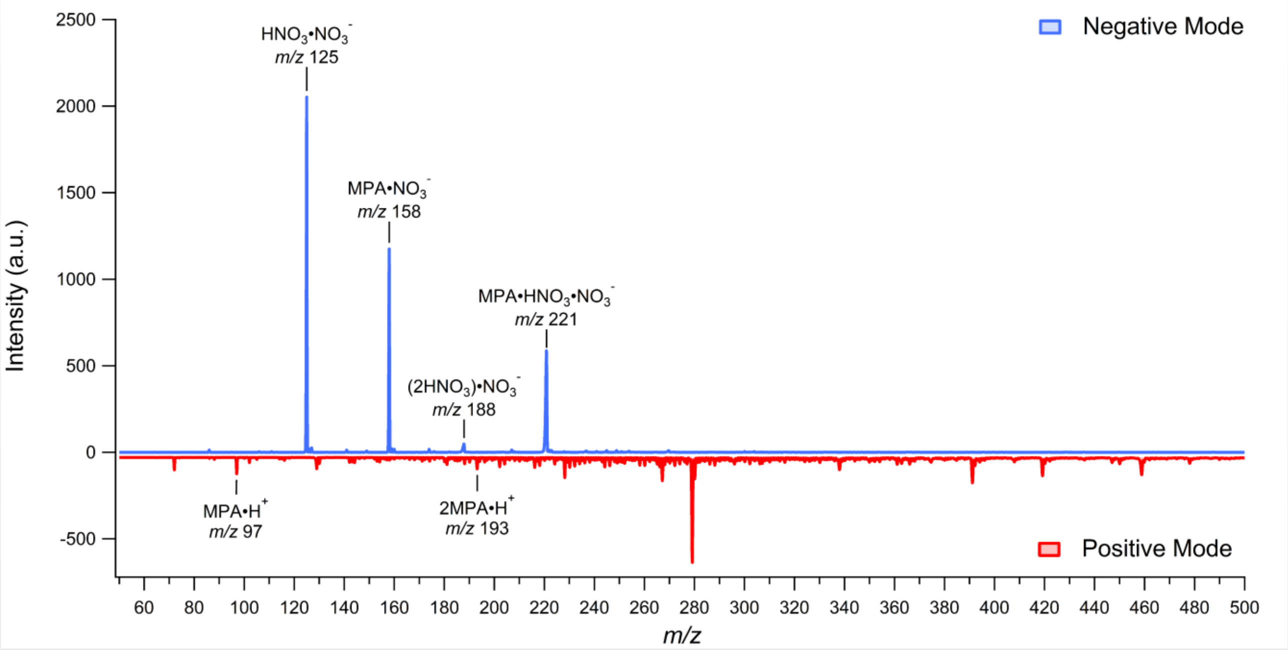
$$[A^-] = [R^-]_0[A]kt$$

k = reaction rate constant (~10^{-9} cm^3 $molecule^{-1}$ s^{-1})
t = reaction time in seconds
[A] = analyte concentration
$[A^-]$ = analyte ion concentration (measured signal)
$[R^-]_0$ = initial reactant ion concentration (measured signal)

1) Ewing et al. *Analytical Chemistry, 85,* **2013**, 389-397. 2) Morrison and Clowers. Characterization of Alkylphosphonic Acid Vapors Using Atmospheric Flow Tube-Ion Trap Mass Spectrometry. *Rapid Comm. Mass Spectrom.*, **2018**. Ahead of print.

How Does AFT-MS Fit in with Vapor Detection?

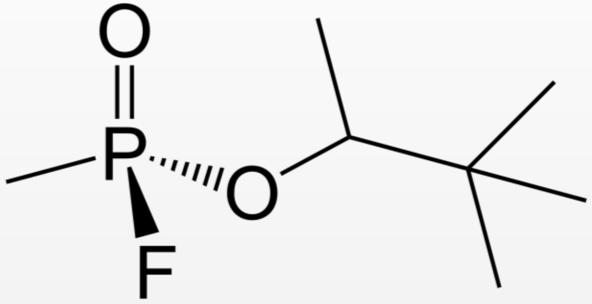
- Both positive and negative analyte ion clusters formed
- Predominant analyte species in negative mode consist of nitrate adducts
- Proton-bound adducts most common for positive mass spectra, generally no specific reactant ion visible



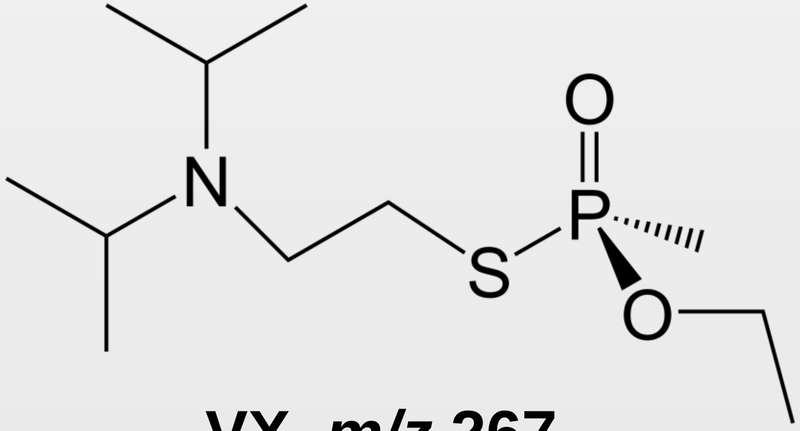
Morrison and Clowers. Characterization of Alkylphosphonic Acid Vapors Using Atmospheric Flow Tube-Ion Trap Mass Spectrometry. *Rapid Comm. Mass Spectrom.*, **2018**. Ahead of print.

CWAs and Their Simulants

- Highly toxic compounds defined by lethality in 50% of test samples (LD_{50}) for single exposures:
  - Oral: <50 mg/kg
  - Inhalation: <50 mg/m^3
  - Skin contact: <200 mg/kg
- Two common CWA species:
  - Soman, G class (fluorine-containing)
  - VX, V class (sulfur-containing)



Soman, *m/z* 182

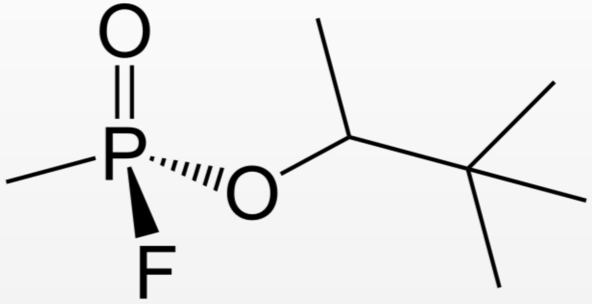


VX, *m/z* 267

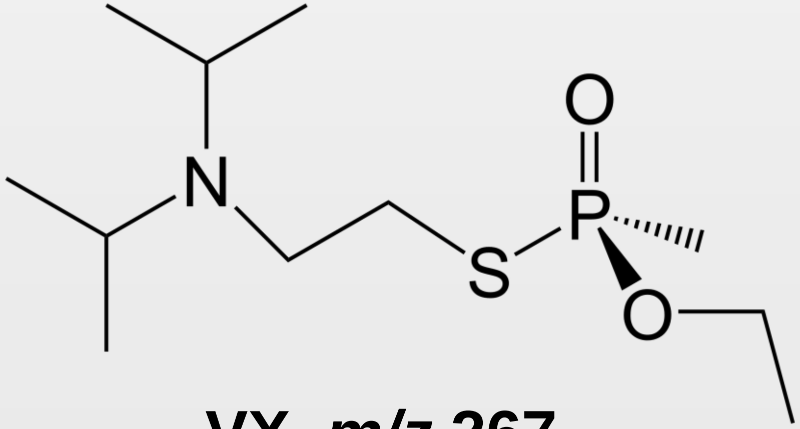
Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives*, *107*, **1999**, 933-974.

CWAs and Their Simulants

- Hazard of CWAs precludes their use in routine method development
- Need to find close analogs to serve as simulants
- Organophosphorus CWAs decompose largely by hydrolysis
- Good starting point to identify simulant species



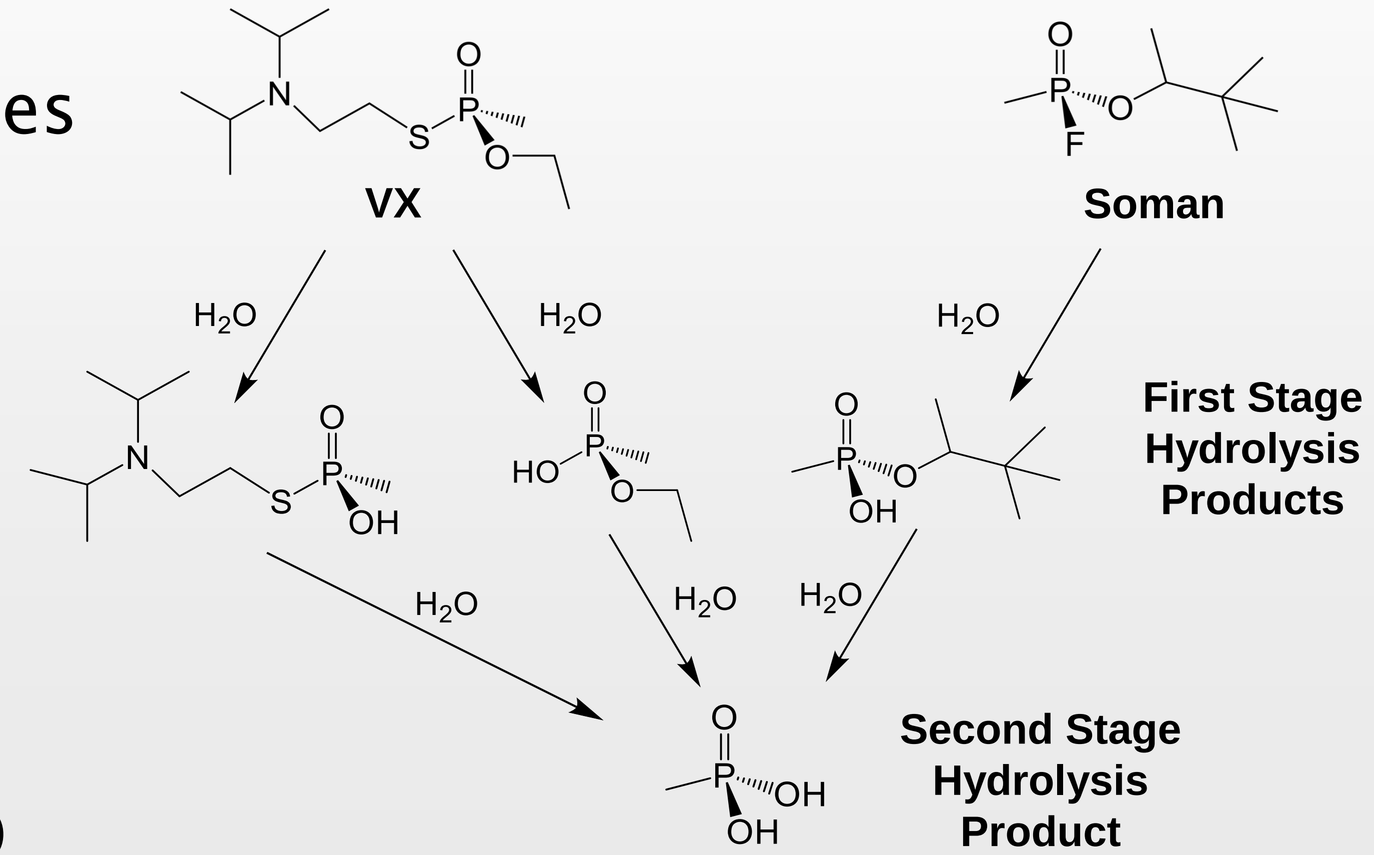
Soman, *m/z* 182



VX, *m/z* 267

CWAs and Their Simulants

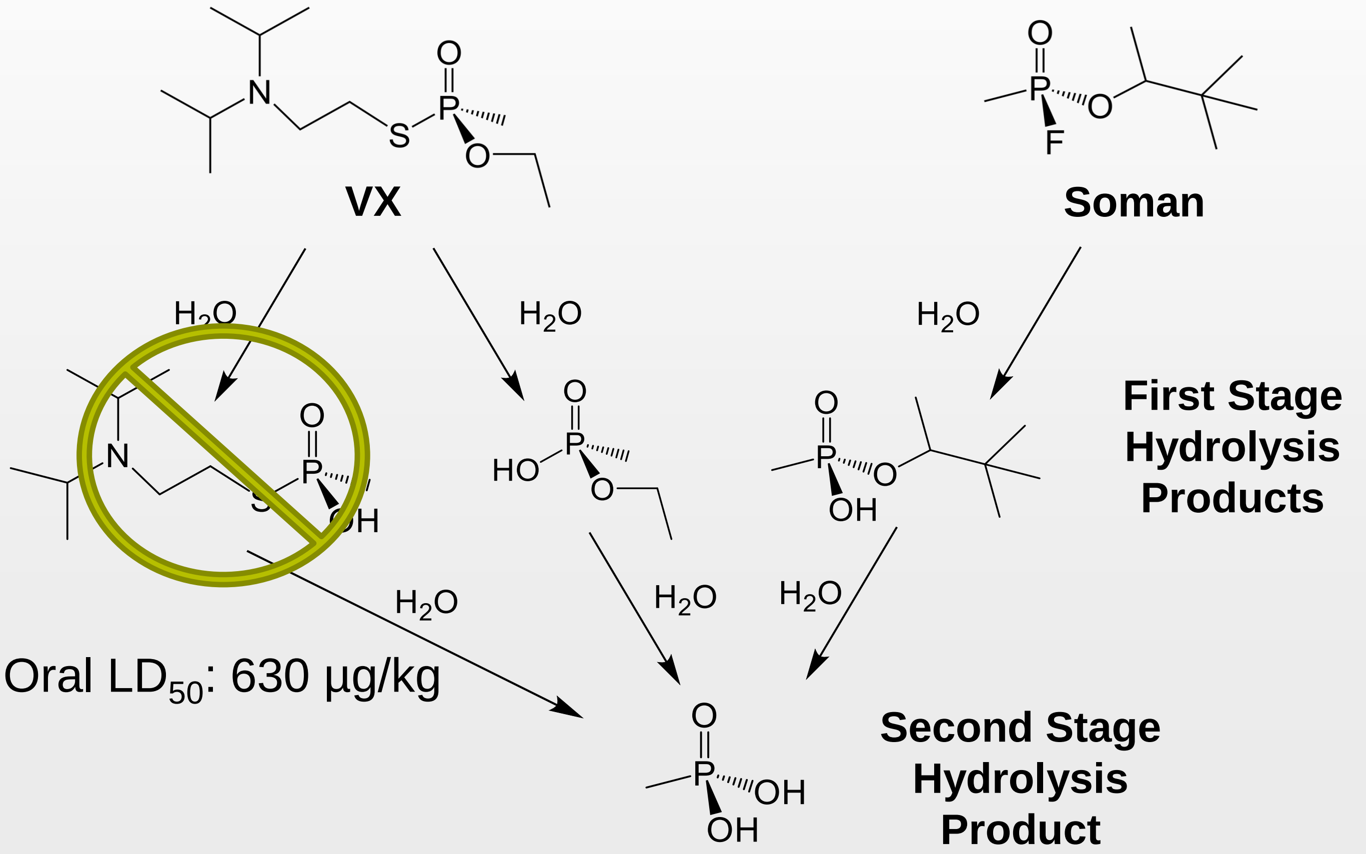
- Hydrolysis of Soman and VX each involves two main stages
  - Both end in methylphosphonic acid (MPA)
- VX has two first hydrolysis products, Soman has one
  - P—F bond more reactive than P—O, while P—S reactivity is similar to P—O



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

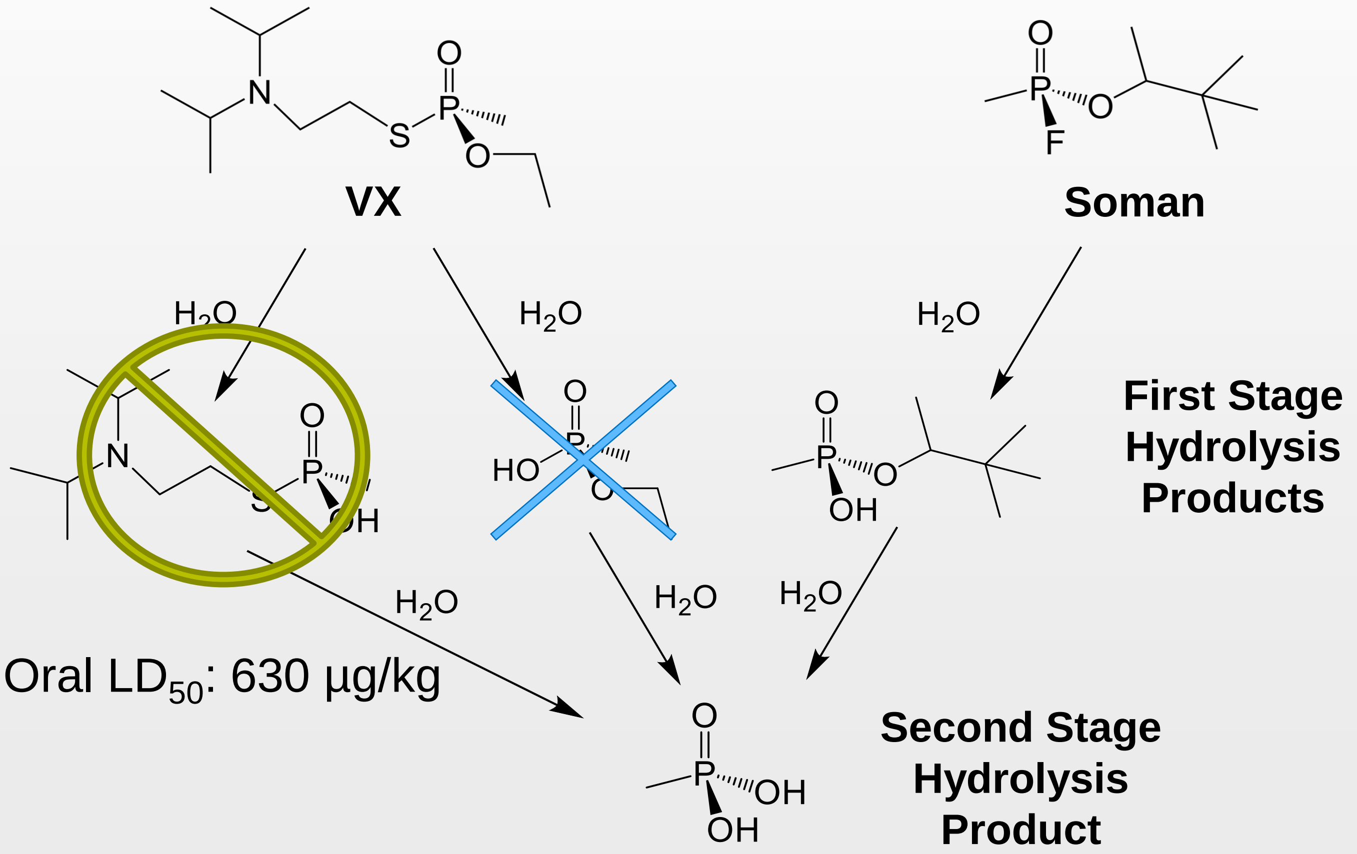
- First hydrolysis of VX can yield a product retaining the P—S bond
- While highly similar to VX, this degradation product is still toxic
  - Rendered unsuitable as simulant of VX



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

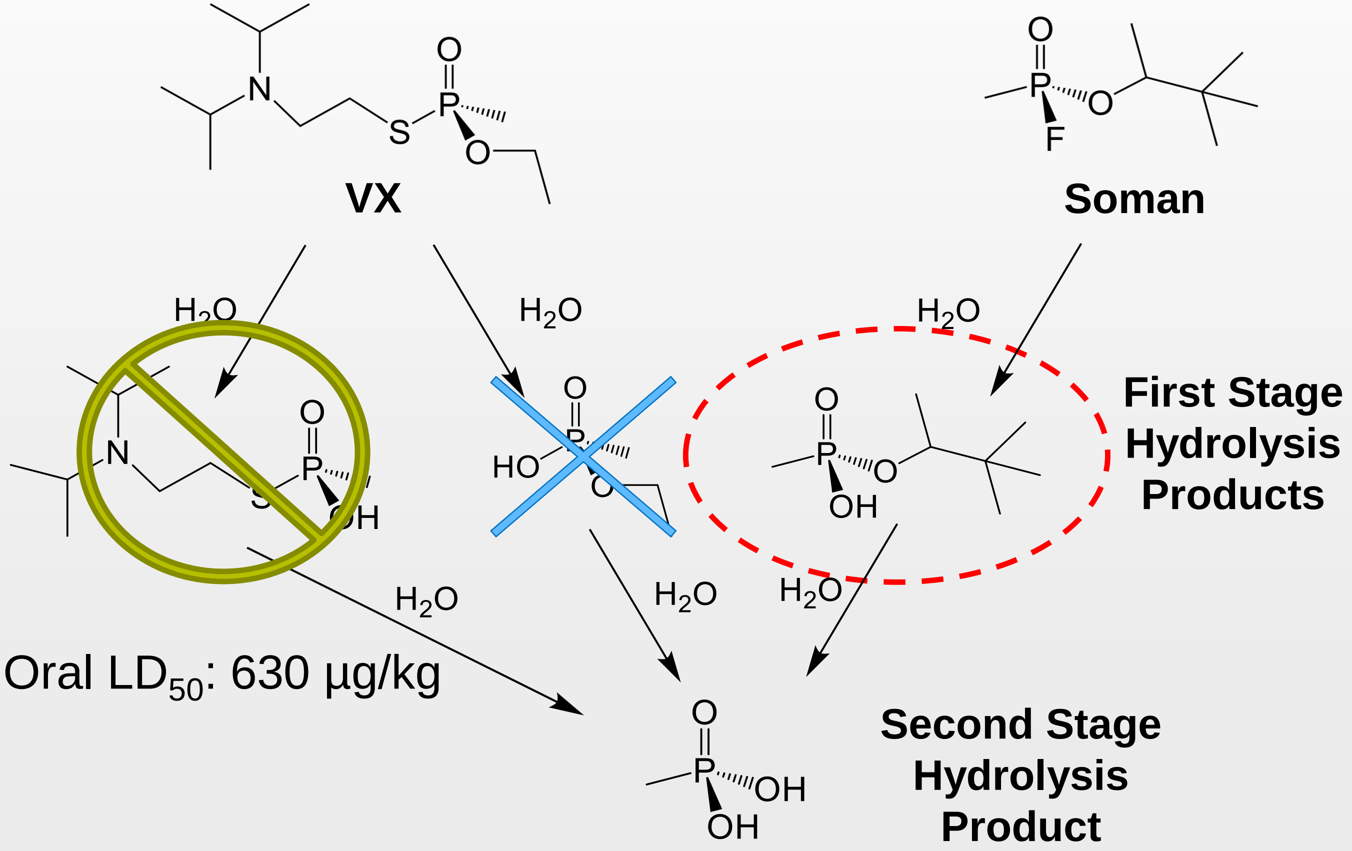
- Other product of first stage hydrolysis of VX is rid of P—S bond
- However, this product is much smaller than VX
  - Unsuitable as simulant due to dissimilarity to VX structure



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

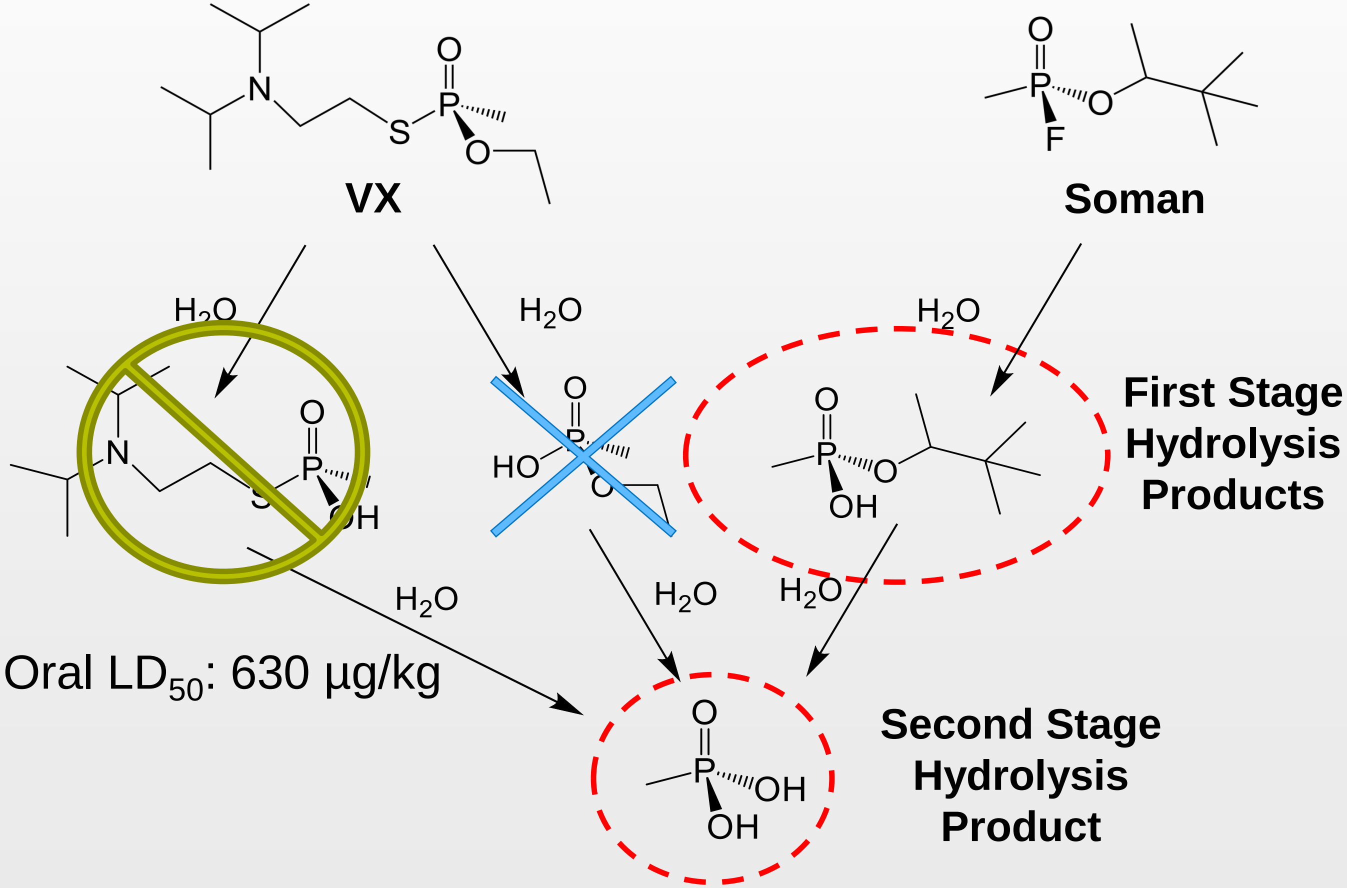
- In contrast, first degradation product of Soman loses the reactive and toxic P—F bond
- Pinacolyl methylphosphonate retains the large alkoxy group from Soman
- Serves as ideal simulant



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

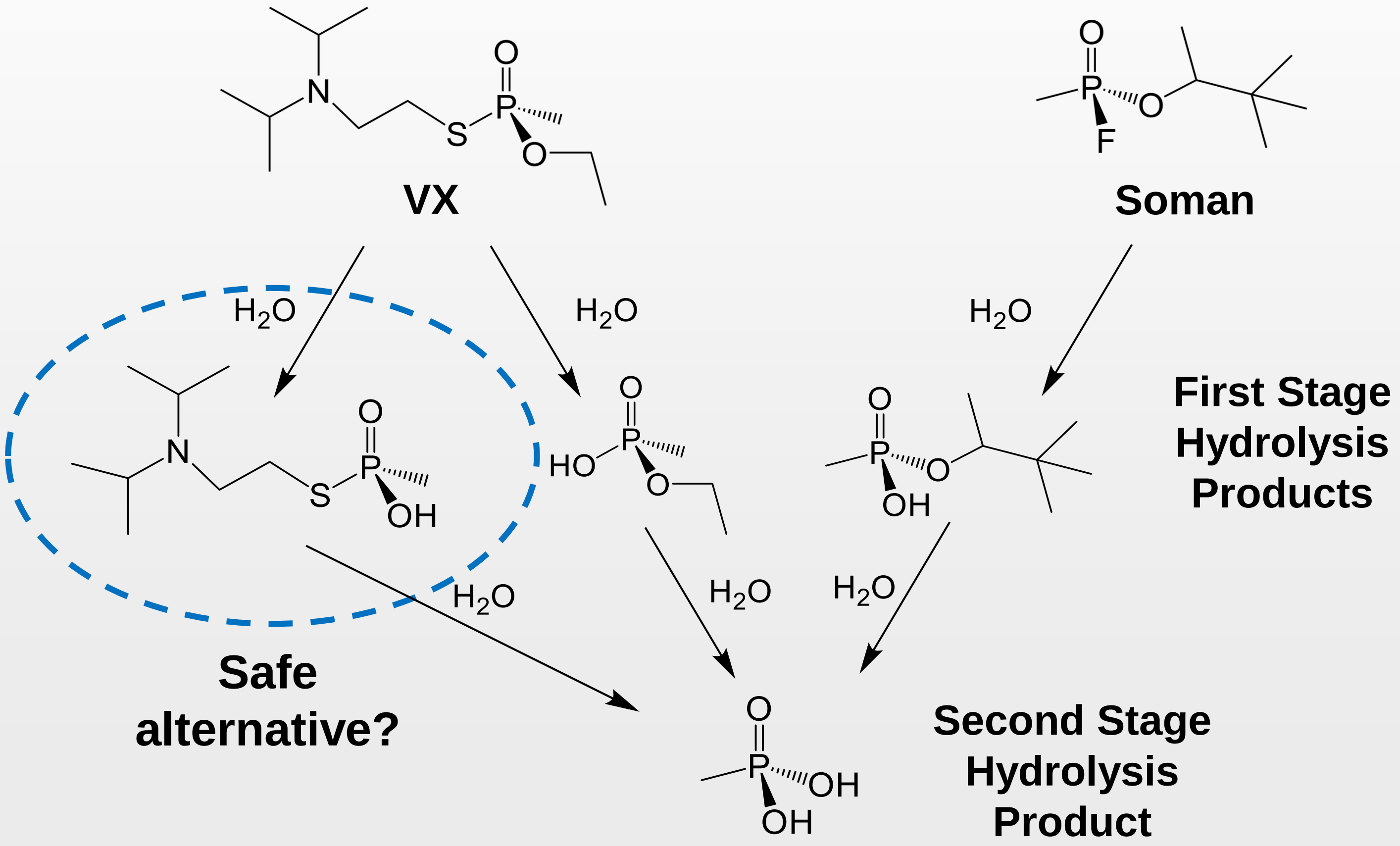
- Second stage of degradation for VX and Soman yields MPA
- MPA can act as indication of recent CWA presence
  - Useful for forensics



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

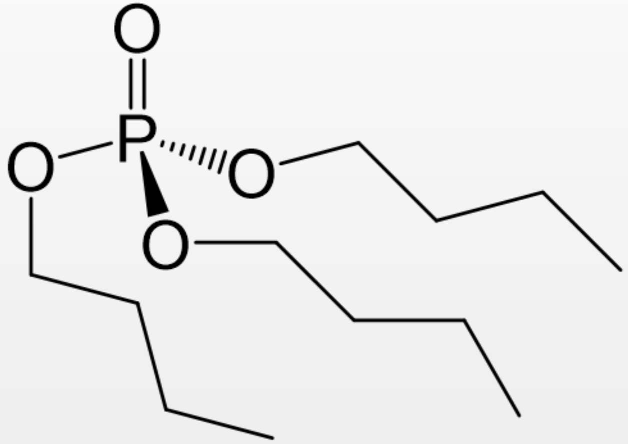
- But what about a simulant for VX that mimics its properties?
- Necessary for preventative method development instead of just post-deployment detection



Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.

CWAs and Their Simulants

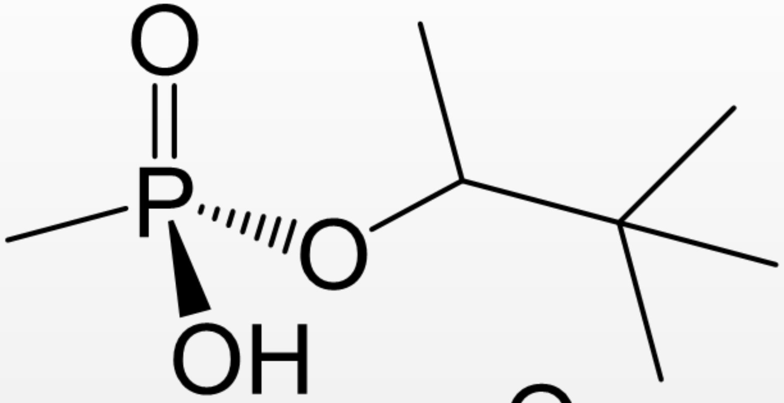
- Other properties an organophosphorus CWA simulant can mimic in addition to structure:
  - Vapor pressure
  - *m/z*
- Tributyl phosphate (TBP) has a similar vapor pressure and *m/z* to VX
- LD_{50} for TBP is >4 orders of magnitude higher in rats than LD_{50} of VX hydrolysis product



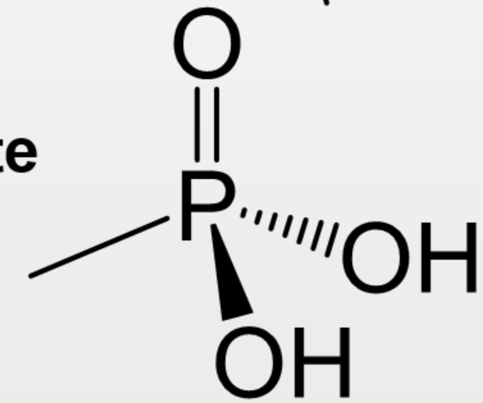
Tributyl Phosphate

Munro et al. The sources, fate, and toxicity of chemical warfare agent degradation products. *Environmental Health Perspectives, 107*, **1999**, 933-974.
Frishman and Amirav. Fast GC-PFPD System for Field Analysis of Chemical Warfare Agents. *Field Analytical Chemistry and Technology, 4,* **2000**, 170-194.

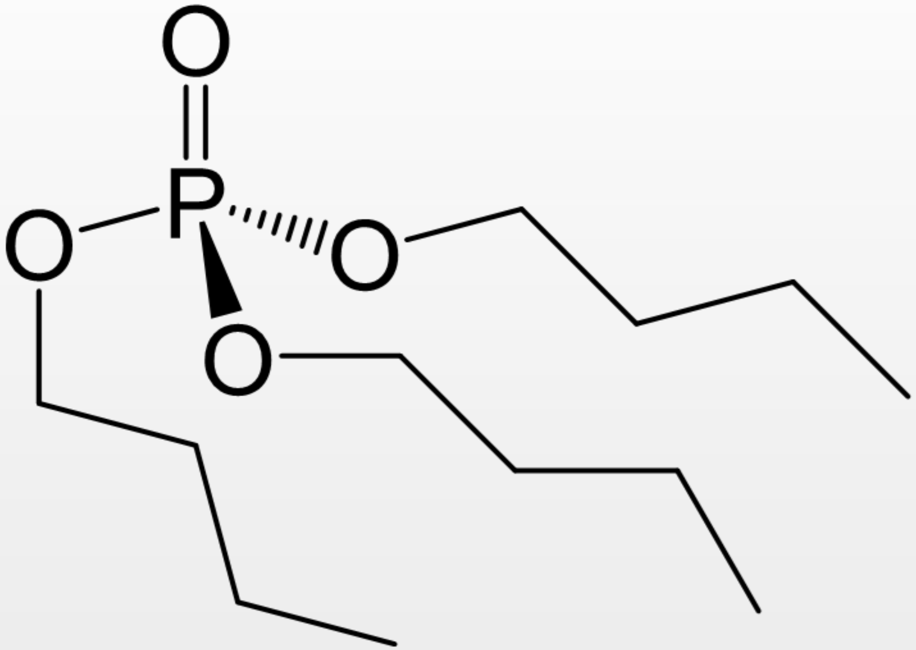
Analytes: Methylphosphonic Acid, Tributyl Phosphate, and Pinacolyl Methylphosphonate



Pinacolyl Methylphosphonate



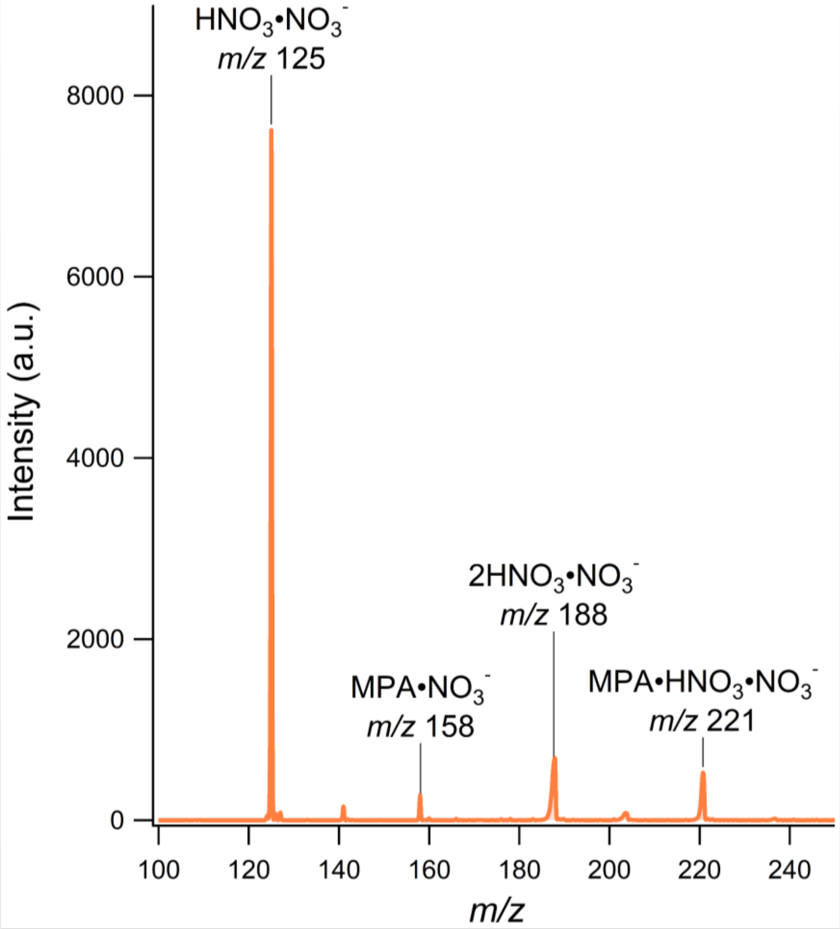
Methylphosphonic Acid



Tributyl Phosphate

MPA Speciation with AFT-MS

- MPA readily forms adducts with nitrate reactant ion species
  - $MPA \cdot NO_3^-$
  - $MPA \cdot HNO_3 \cdot NO_3^-$



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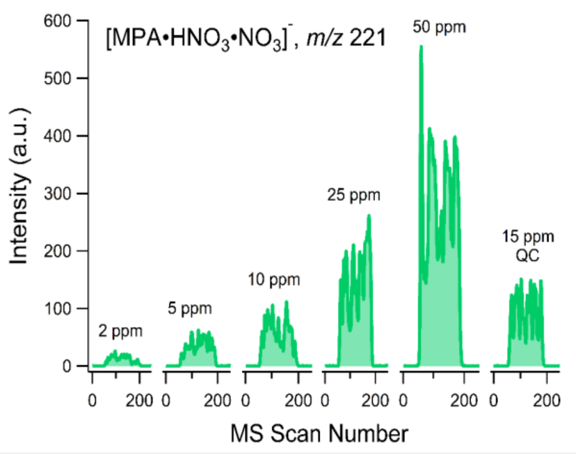
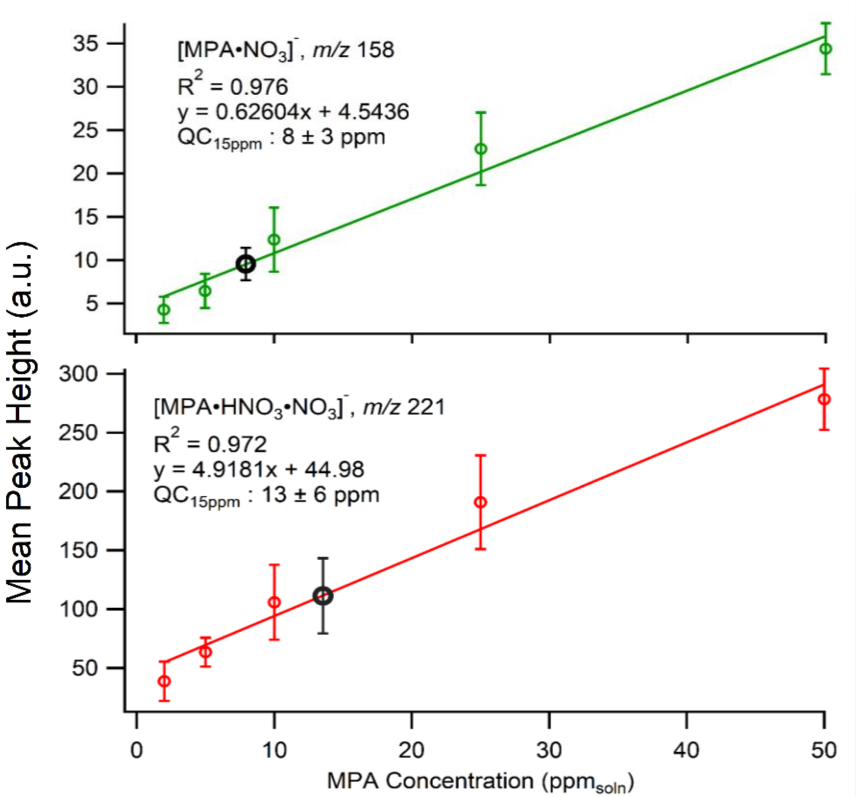
MPA Quantitation with AFT-MS

- $MPA \cdot HNO_3 \cdot NO_3^-$ and $MPA \cdot NO_3^-$ adducts both exhibit good linearity
- However, the $MPA \cdot HNO_3 \cdot NO_3^-$ trendline provided more accurate QC solution concentration from *headspace* signal





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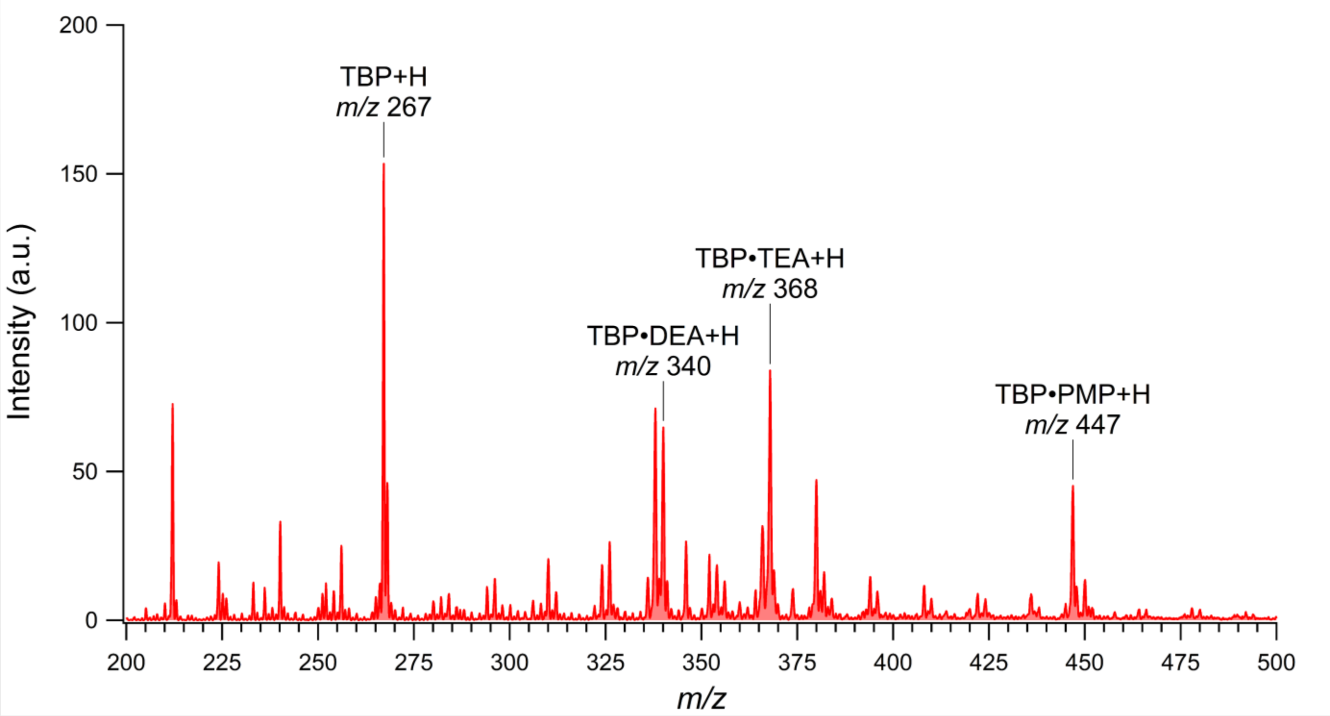
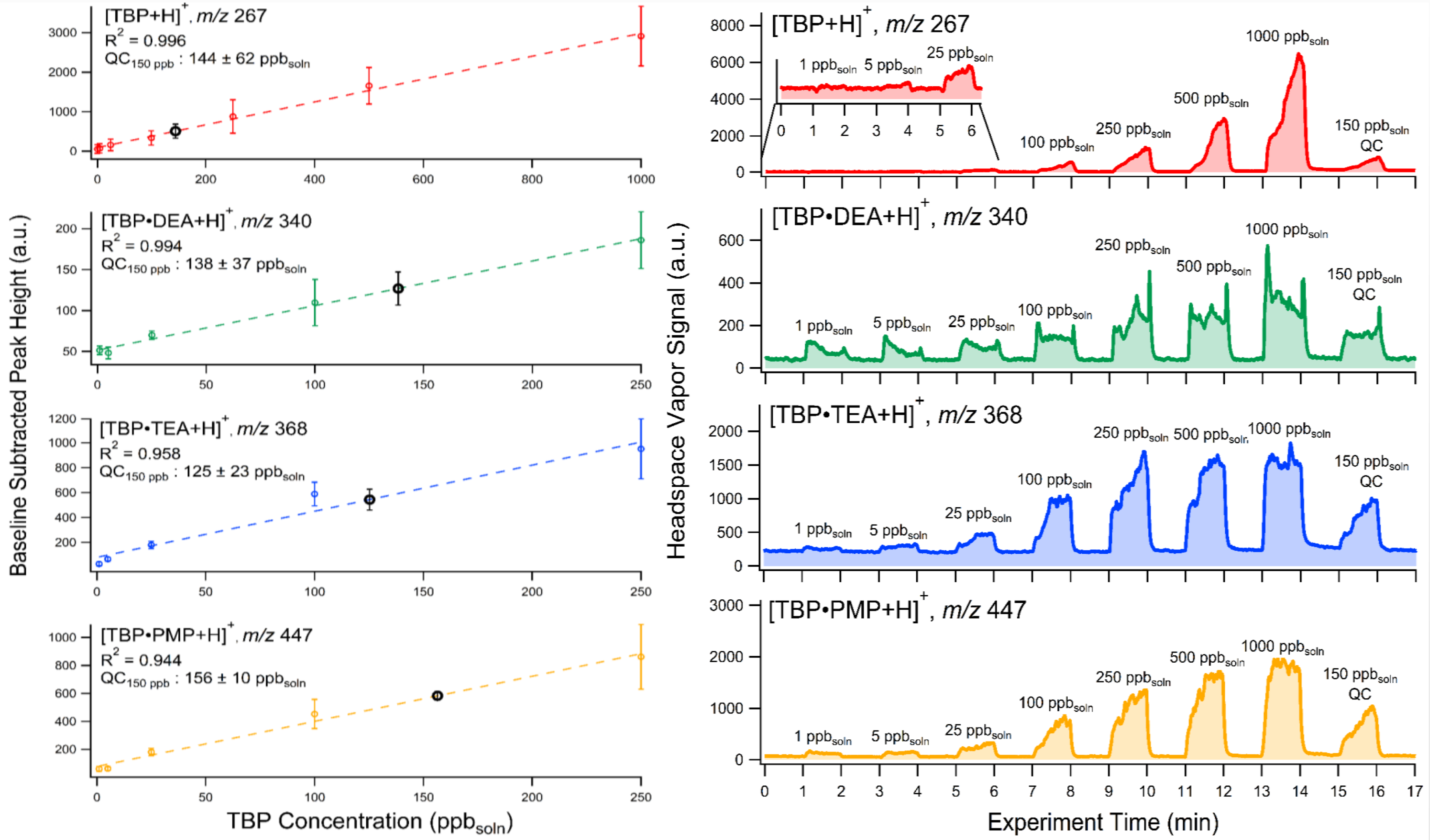
TBP Speciation with AFT-MS

- TBP is visible as a protonated species as well as a proton-bound heterodimer with high proton affinity dopant molecules
- Dopants chosen here include diethylamine (DEA), triethylamine (TEA), and PMP



Morrison, Ewing, and Clowers. Ambient Vapor Sampling and Selective Cluster Formation for the Trace Detection of Tributyl Phosphate via Atmospheric Flow Tube Mass Spectrometry. Manuscript in preparation.

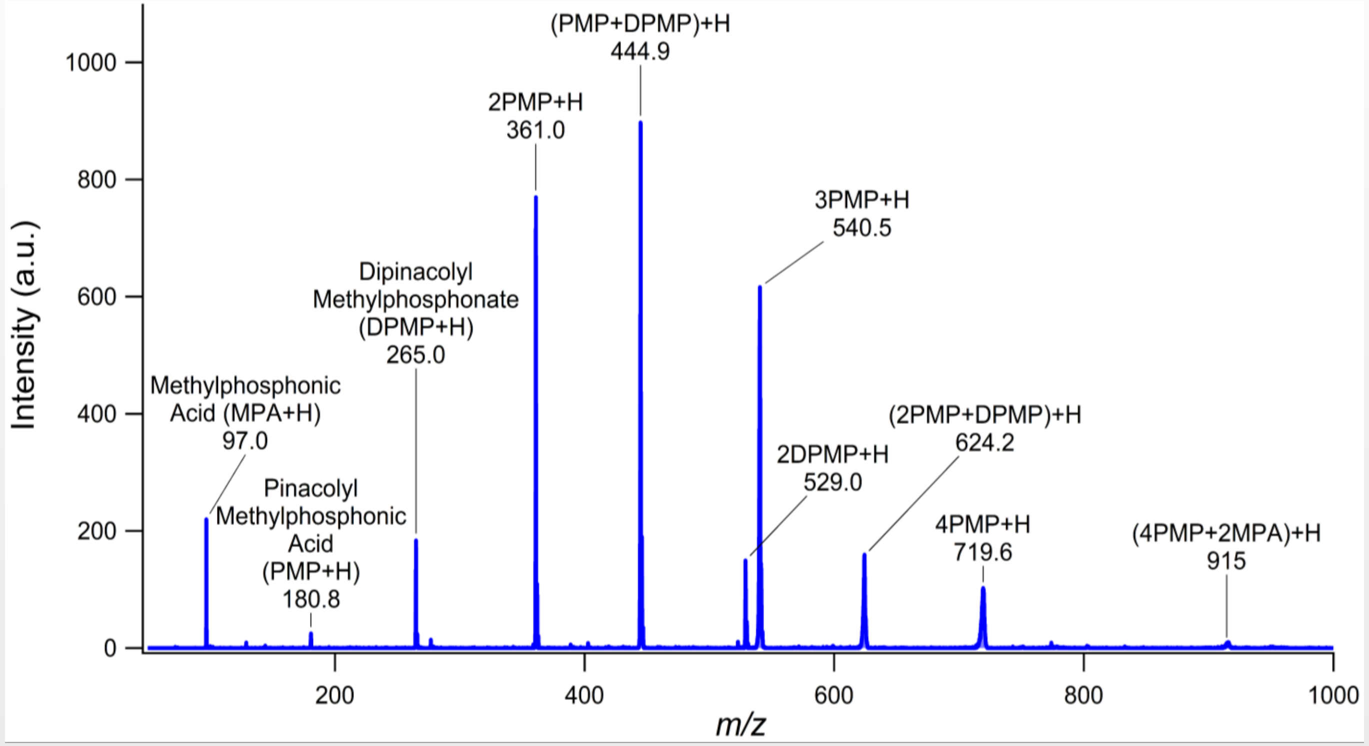
TBP Quantitation with AFT-MS



Morrison, Ewing, and Clowers. Ambient Vapor Sampling and Selective Cluster Formation for the Trace Detection of Tributyl Phosphate via Atmospheric Flow Tube Mass Spectrometry. Manuscript in preparation.

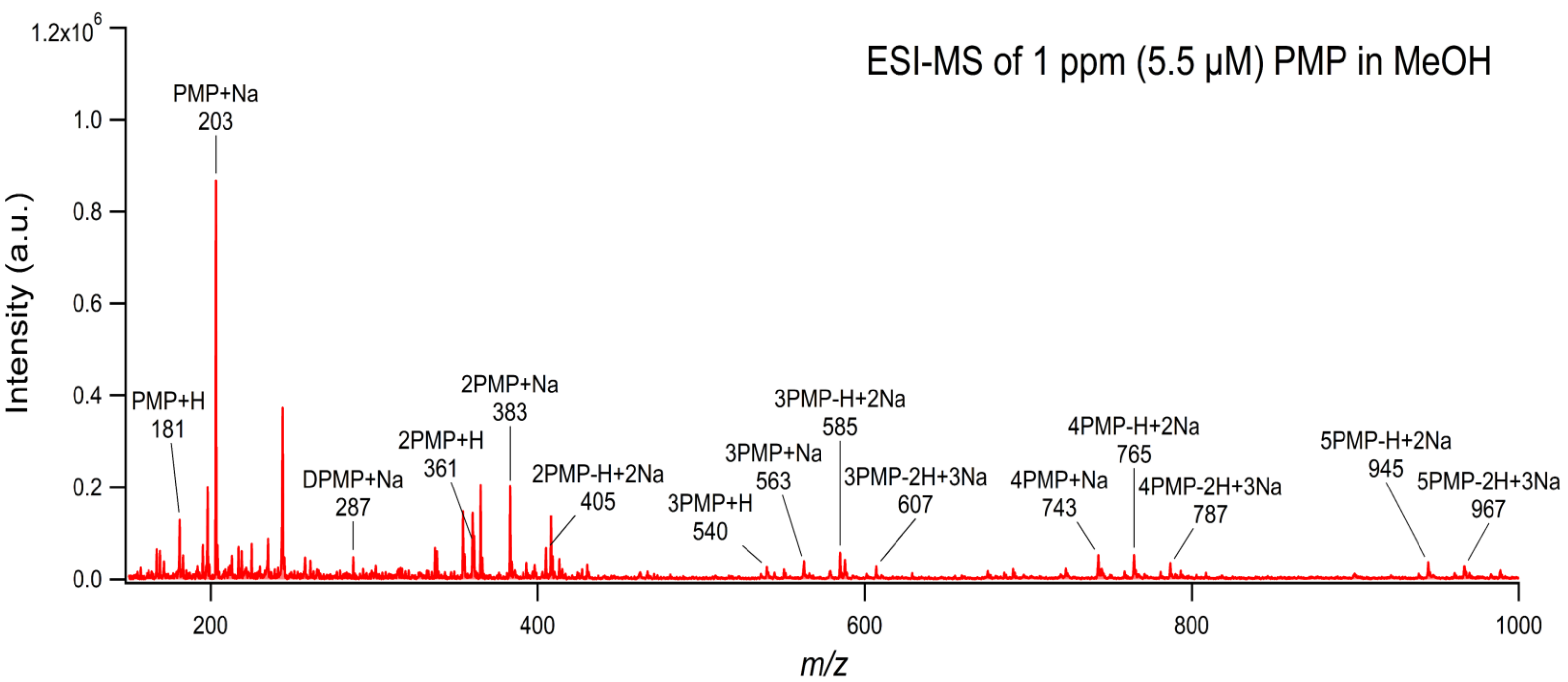
PMP Speciation with AFT-MS

- PMP exhibits extensive self-clustering in the gas phase
- Other species found include MPA and dipinacolyl methylphosphonate, neither of which was added to the sample
  - Suspected to be forming during travel in flow tube



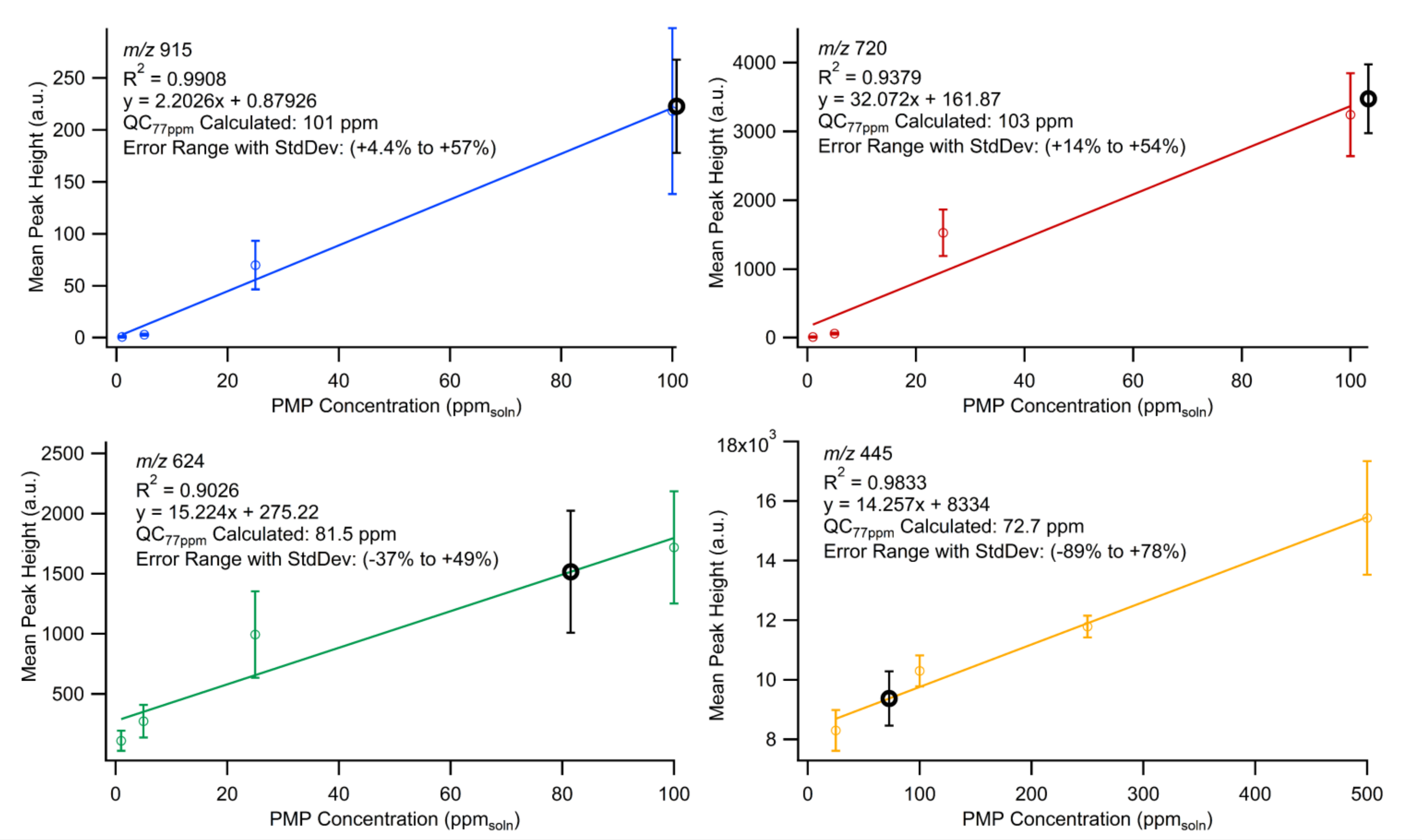
PMP Speciation with AFT-MS

- Electrospray-MS of PMP also yields multimeric species
  - Adducts with sodium
- However, the signal for DPMP is minimal and nonexistent for MPA
  - Supports idea of formation in AFT



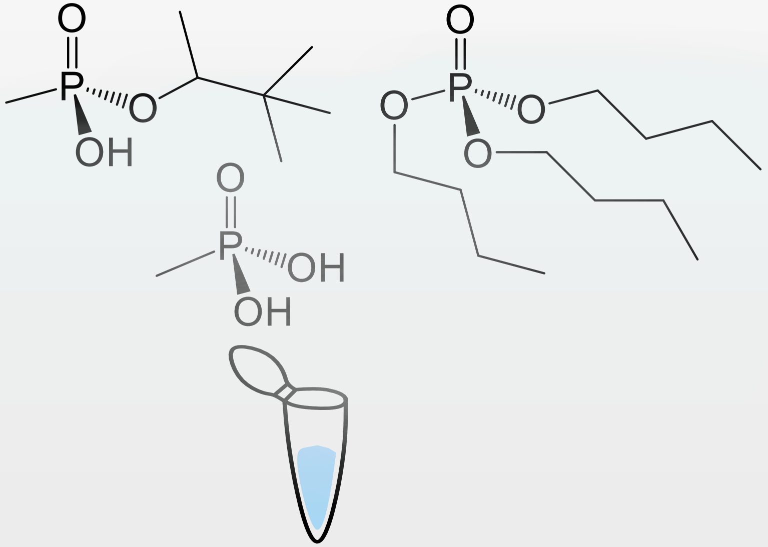
PMP Quantitation with AFT-MS

- Having PMP signal split can create non-linear behavior for some species
- Only four adducts produced linear regression lines
  - QC errors were high
- Possible solution is to lower PMP concentration



Recap of AFT-MS for Headspace Sampling

- Solution phase CWA simulant concentrations were estimated by non-contact sampling of headspace vapor by AFT-MS
- Excellent specificity of AFT-MS analyte identification confirms its applicability for CWA simulant sensing
- Future pursuits include sampling from other solvents and from surfaces



Acknowledgments

Funding and Support

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Clowers Research Group