Aerosol Interaction with Individual Protective Equipment (IPE)

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Outline

• Problem
• Background
  – Aerosols
  – Driving force: air movement
• Test technology design
• Investigations
  – Literature review
  – Operationally-focused elevated wind study
  – S&T elevated wind study
• Summary
Problem

- IPE protective mechanisms that are effective against vapor or liquid agents may be ineffective against aerosols
- Protection against aerosols pose a complex set of issues
Relevance

- **Impact operational planning**: review of existing Tactics, Techniques, and Procedures (TTP)

- **Provide basis for developing validated test technology**: evaluate advanced IPE incorporating protection in high winds (e.g., JPACE block 2)

- **Transition into testing**: e.g., JSLIST NTA tests

- **Provide otherwise unavailable data**: validate IPE model simulations (input into JPM-IP modeling & simulation efforts)
Background

- **Aerosol**: Assembly of liquid or solid particles suspended in gaseous medium long enough to be observed or measured (~0.001 – 100 µm)
- **Agglomerate**: Group of particles bound together by van der Waals forces or surface tension
- **Particle size**: diameter of spherical particle (theoretical) having same value of specific property as irregularly shaped particle (actual)
  - **Aerodynamic Diameter**: diameter of theoretical sphere (density = 1.0) having same gravitational settling rate as actual particle
  - **Size distribution**: spread of particle sizes in aerosol

Relationship between actual particle morphology and equivalent aerodynamic diameter *Corn, (1968)*

Aggregate structure at increasing resolution *Willeke & Baron (1993)*
Change in mean particle size and number as a function of time

\[ \frac{dN}{dt} = -KN^2 \]

Smoluchowski (1917)

\( N = \) number
\( t = \) time
\( K = \) Coagulation coefficient

<table>
<thead>
<tr>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>10 nm</th>
<th>100</th>
<th>1000</th>
<th>10,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 nm</td>
<td>67</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>180</td>
<td>8.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1700</td>
<td>24</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>16000</td>
<td>220</td>
<td>10.3</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

Coagulation coefficient \( K \times 10^{10} \, \text{cm}^3/\text{s} \) for colliding aerosol particles of diameters \( D_1 \) and \( D_2 \) (nm) (Hinds, 1982)
Background

Approximate sizes of representative natural and synthetic aerosols
Aerosol Penetration Mechanisms

Driving forces:
- hydrostatic pressure gradient (e.g., wind)
- concentration gradient
- temperature gradient

Influencing factors:
- particle inertia (m\cdot v)
- \( \Delta p_i / \Delta d_j \)
- fabric geometry
- diffusion coefficient
- solubility

Deposition mechanisms
Nature of wind

Natural wind (meteorological)

Vehicle generated (e.g., rotorwash)

Motion generated (e.g., tank commander)
Goals

Characterize the effects of aerosols & wind on personnel CB exposure and ultimately physiological risks

• Define extent of operational risk
  – Threat (e.g., agents, concentration, wind speed, missions)
  – Mission impact, numbers affected
  – Likelihood of occurrence

• Establish extent of potential IPE limitations
  – Clothing
  – Masks
  – Filters

• Characterize operational conditions impacting IPE limitations
  – Body movements, physical tasks
  – Physiological demands (e.g., respiration, metabolism, sweating)
  – POL
  – Environmental conditions (e.g., dirt, dust, rain)
Independent variables

- **Standardized test method**
  - Laboratory (e.g., wind tunnels)
  - Field testing

- **Challenge**
  - Agent
    - neat vs. weaponized vs. simulant(s)
    - Vapor vs. liquid vs. aerosol
  - Dissemination (point vs. line source, ground)
  - Aerosols:
    - Liquids
    - Solids: particle size & distribution

- **Wind source** (e.g., rotor, wind tunnel, fan)

- **Penetration/Deposition**
  - Tagging challenge
  - Sampling
  - Quantitative analysis
Approach

• Characterize conditions external to IPE
  – Wind speed & characteristics (e.g., pressure, pulsatile vs. steady flow)
  – Challenge concentration at IPE surface
  – Challenge characteristics (e.g., aerosols, vapors)

• Define impact of IPE characteristics
  – Material properties (e.g., pore size)
  – Closures, interfaces
  – Inner layers

• Characterize penetration pathways

• Quantify deposition on surfaces exposed to sweat (skin, inner clothing layer)
Literature Review

Aerosol Deposition

• < 10 µm mass mean diameter (MMD) can penetrate IPE
• Skin deposition increases as wind speed increases with particle MMD < 3.0 µm
• Skin deposition increases with ambient temp
• RH may not affect skin deposition
• Increasing body hair increases skin deposition

Reviewed available technical literature on wind-driven CB effects on IPE, including test methodologies and agent physiochemical properties: assess technical strengths and weaknesses of work (Documents referenced: 71)
**Literature Review: Findings**

Figure 1. Summary of Unclassified Deposition Velocity Data  
(Particle Size Range: 1-3 mm)

**Relationship between wind speed, IPE, and deposited aerosol mass**  
(literature values)

<table>
<thead>
<tr>
<th>1980-CPO: Chemical IPE ca.1980s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BDO/ BDU/under:</strong> Battledress overgarment over battledress uniform &amp; underwear</td>
</tr>
<tr>
<td><strong>BDO/under:</strong> BDO &amp; underwear</td>
</tr>
</tbody>
</table>
| **MKIII/CD/under:** Navy chemical IPE over chambray shirt, denim trousers & underwear.  
  *Chinn (2004)* |

**Deposition Velocity**  
\[
V_d = \frac{m_{\text{deposited}} - m_{\text{background}}}{A_{\text{sample}} \cdot C_m \cdot T}
\]

- \(V_d\): Deposition Velocity  
- \(m_{\text{deposited}}\): Deposited aerosol mass  
- \(m_{\text{background}}\): Background aerosol mass  
- \(A_{\text{sample}}\): Surface area of sample  
- \(C_m\): Mass concentration  
- \(T\): Exposure time
**Study Goals**

**Block I**
- Determine impact of wind speed on aerosol entrainment in IPE layers and skin deposition
- Determine wind speeds resulting in least and greatest aerosol penetration

**Block II**
- Determine if field-expedient system modifications can mitigate wind speed effects
- Determine the effect of exposure time & wind speed on aerosol penetration of IPE
# DO-49 study: Test matrix

<table>
<thead>
<tr>
<th>Block</th>
<th>Scenario</th>
<th>Configuration</th>
<th>Exposure Time (min)</th>
<th>Wind Speed (mph)</th>
<th>Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block I</td>
<td>1</td>
<td>IPE None</td>
<td>10</td>
<td>0 to 2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>IPE None</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>IPE None</td>
<td>10</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>IPE None</td>
<td>10</td>
<td>~40</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>IPE None</td>
<td>3</td>
<td>P+(^b)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>IPE Taped(^c)</td>
<td>10</td>
<td>P-(^d)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>IPE Taped</td>
<td>10</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>IPE Untaped, Poncho</td>
<td>10</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>IPE Untaped, Rain Gear (Wet Weather)</td>
<td>10</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>IPE Taped Rain Gear (Wet Weather)</td>
<td>10</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>IPE + BDU None</td>
<td>10</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>IPE None</td>
<td>30</td>
<td>P+</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>IPE None</td>
<td>10 chamber 20 clean room(^e)</td>
<td>P+</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^a\) BDU – battledress uniform  
\(^b\) Block I wind speed causing most aerosol penetration  
\(^c\) All configurations taped on outside garment  
\(^d\) Block I wind speed causing least aerosol penetration  
\(^e\) 10 min. in chamber at wind speed P+, 20 minutes in clean room
DO-49 study: Test conditions

<table>
<thead>
<tr>
<th></th>
<th>mean</th>
<th>SEM</th>
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<tbody>
<tr>
<td>Mass Median Diameter (mm)</td>
<td>2.72</td>
<td>0.08</td>
</tr>
<tr>
<td>Geometric Standard Deviation</td>
<td>2.52</td>
<td>0.09</td>
</tr>
<tr>
<td>Average mass concentration (mg/m³)</td>
<td>188.1</td>
<td>8.2</td>
</tr>
<tr>
<td>CT (mg m⁻³ min)</td>
<td>1976.6</td>
<td>145.6</td>
</tr>
<tr>
<td>Average Temp (°F)</td>
<td>74.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Average RH (%)</td>
<td>43.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Wind Speed (mph)
- 3
- 10
- 20
- 40

Environmental and simulant conditions

Skin & material sampling sites
**DO-49 elevated wind study:**
Results of wind speed/garment combinations

Skin deposition of aerosol simulant:
UV illumination of Fluorescent tag

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**Deposition by layer**
- liner roughly 10-fold less deposition than outer surface
- tee shirt, socks roughly equivalent
- other layers variable, generally much less
Current JSTO study: Effects of elevated wind speed on agent penetration of IPE

**Objectives**: Correlate elevated wind speeds (above 10 mph) with aerosol penetration of IPE materials and systems

**Approach**:
- Develop techniques to disperse and characterize submicron aerosol in wind tunnel *(task 1)*
- Assess aerosol penetration of materials and system components (e.g., sleeves) *(task 2)*
- Assess how IPE system design affects aerosol penetration *(task 3)*
Task 1 – Wind Tunnel Characterization:

*Objective:* characterize aerosol dispersal in a wind tunnel

- Air stream
- Target surface (IPE material, component, or system)

• Particulate tagging
• Aerosol characterization
  - particle size & size distribution
  - tag distribution
• Swatch penetration (RTI)
  - Liquid vs. solid phase aerosols (0.02 - 1.0\(\mu\)m)
  - Variable pressure gradient (wind speed)
• Dissemination, wind tunnel
• Characterization, wind tunnel

RTI swatch test fixture: aerosol penetration in wind
**Effects of elevated wind speed on agent penetration of IPE**

**Particle Tagging:** Understand particle surface chemistry regarding tag adsorption and agglomeration

- Covalent bonding of fluorescent material with fumed silica particle

**Filtration:** Quantify filter properties of IPE in flow field and compare with M&S

- Most penetrating particle size
- Aerosol/material interaction: solid vs. liquid particles
- Filter efficiency as function of
  - particle size
  - pressure (velocity)
  - IPE material
- Mass flux across IPE layers
  - Windward vs. leeward deposition
  - Mass transport through all layers
Effects of elevated wind speed on agent penetration of IPE

Swatch sample: outer shell & inner liner

<table>
<thead>
<tr>
<th>Fabric Pressure Drop (&quot; H2O)</th>
<th>Face Velocity (cm/s)</th>
<th>Wind Speed (mph)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.57 - 0.91</td>
<td>14</td>
</tr>
<tr>
<td>0.5</td>
<td>3.14</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>13.14</td>
<td>64</td>
</tr>
</tbody>
</table>

Relationship between fabric pressure drop, face velocity through the fabric, and upstream wind speed*.

* Wind speed (for this table) = ambient wind speed needed to create a velocity pressure equal to the fabric pressure drop

RTI swatch test fixture: aerosol penetration in wind
Airstream characteristics
Deposition mechanisms at varying wind speeds and particle sizes
- Fine particles (<1.0 µm): diffusion & interception
- Std aerosol test (RTI) particles (~ 2.5 µm): interception & impaction predominate

Hinds, 1999
**JSTO Elevated wind speed: Phase 1 results**

**Swatch penetration**
- Liquid vs. solid aerosol
- Particle size
- Pressure drop
  - 0.1” (14 mph)
  - 0.5” (32 mph)
  - 2.0” (64 mph)

\[ P_{\text{obs}} = \frac{C_{\text{downstream}}}{C_{\text{upstream}}} \]

**Results**
- Peak penetrating particle size (approx. 0.08 – 0.25µm, vel. dep.)
- Max. penetration (approx. 50-70%, vel. dep.)
- Note: non-penetrating aerosol fraction depositing on/in fabric
Reproducibility
Results from 3 independent trials at 0.1” pressure drop

Figure 4. Penetration versus particle diameter for the triplicate fabric swatches at 0.1” fabric pressure drop with: a) KCl aerosol and b) oleic acid aerosol.
**JSTO Elevated wind speed: Aerosol dispersion**

**Prototype aerosol dissemination**
A - Spray system with Laskin nozzle
B - Dispersion box; *Inset: With top removed*
C - Dispersion System mounted in NATF
   *Inset: Rear of system*
Summary

- Aerosolized agents can overcome IPE protection
- Quantifying IPE limitations needs to account for:
  - Mass transport mechanism
    - Magnitude of driving force
  - Particle inertia
    - Particle size & mass
# Acknowledgements

Individuals responsible for the success of this work include:

<table>
<thead>
<tr>
<th>Literature Review:</th>
<th>DO-49 study:</th>
<th>JSTO study:</th>
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<tbody>
<tr>
<td>Dr. Kenneth Chinn</td>
<td>Jean Baker</td>
<td>Dr. Tom Cao</td>
</tr>
<tr>
<td>Stephen Coleman</td>
<td>James Hanzelka</td>
<td>Terence Ghee</td>
</tr>
<tr>
<td>Teresa Kocher</td>
<td>Nathan Lee</td>
<td>James Hanley</td>
</tr>
<tr>
<td>Maura Rudy</td>
<td>Grant Price</td>
<td>James Hanzelka</td>
</tr>
<tr>
<td>Kathy Schaneveldt</td>
<td>Charlie Walker</td>
<td>Dr. Chris Olson</td>
</tr>
</tbody>
</table>

_Sponsor: JPACE_  
_Sponsor: JSIG_  
_Sponsor: JSTO_  
*(Tony Ramey, CAPO)*
Questions?
Backup slides
**Rotorwash effects**

Effect of wind & challenge dissemination
(DSTL 2002 study)
## Literature Review

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Ref #</th>
<th>Year</th>
<th>Primary Author</th>
<th>Wind Speed (knots)</th>
<th>Protective Outergarment</th>
<th>Primary Focus</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG, solid</td>
<td>1</td>
<td>1949</td>
<td>Wagner</td>
<td>4.1 - 26.0</td>
<td>Butyl coated cloth</td>
<td>Ss in tunnel</td>
<td>Penetration increases with wind</td>
</tr>
<tr>
<td>VX, 9-12 μm, liquid</td>
<td>2</td>
<td>1969</td>
<td>Dawson</td>
<td>11.3</td>
<td>1967-CPO</td>
<td>Manikin in tunnel</td>
<td>Penetration increases with wind</td>
</tr>
<tr>
<td>Oleic acid, 0.7 μm, liquid</td>
<td>3</td>
<td>1988</td>
<td>Hanley</td>
<td>14</td>
<td>1980-CPO</td>
<td>Ss sleeves only</td>
<td>Penetration increases with wind &amp; decreasing particle size</td>
</tr>
<tr>
<td>AFL, 0.5 μm, liquid</td>
<td>4</td>
<td>1989</td>
<td>Hanley</td>
<td>8.7-34.8</td>
<td>CPO</td>
<td>Manikins with taping</td>
<td>Penetration increases with wind; upwind greater than downwind</td>
</tr>
<tr>
<td>TEG, 1 &amp; 3 μm</td>
<td>7</td>
<td>1990</td>
<td>Hanley</td>
<td>8.7-34.8</td>
<td>CPO</td>
<td>Manikins, raingear</td>
<td>Penetration increases with wind</td>
</tr>
<tr>
<td>NaCl, 1-3 μm</td>
<td>8</td>
<td>1991</td>
<td>Tytus</td>
<td>2.6-7.8</td>
<td>CPO</td>
<td>Manikins</td>
<td>Penetration increases with wind</td>
</tr>
<tr>
<td>TEG, 0.5 &amp; 2 μm</td>
<td>9</td>
<td>1999</td>
<td>Engels, Gibbs</td>
<td>4.3-26.0</td>
<td>Navy CPO (Mk III)</td>
<td>Manikins</td>
<td>Penetration increases with wind</td>
</tr>
<tr>
<td>Syloid, 3.0 μm, solid</td>
<td>10</td>
<td>1994</td>
<td>Chinn</td>
<td>2.3-16.3</td>
<td>BDO</td>
<td>Manikins, field test</td>
<td>Penetration increases with wind</td>
</tr>
</tbody>
</table>

* - Aerosol, ^ - particle size unreported, * - mass mean diameter, TEG - tetraethylene glycol, AFL - ammonium fluorescein