Aerosol Interaction with Individual Protective Equipment (IPE)

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Making the World Safer

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

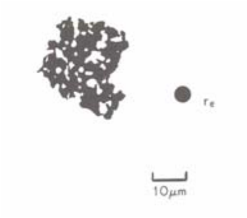
- IPE protective mechanisms that are effective against vapor or liquid agents may be ineffective against aerosols
- Protection against aerosols pose a complex set of issues

Relevance

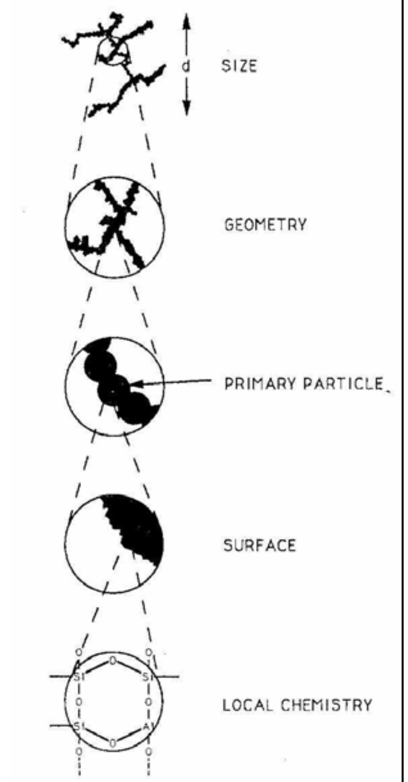
- **Impact operational planning**: review of existing Tactics, Techniques, and Procedures (TTP)
- **Provide basis for developing validated test technology:** evaluate advanced IPE incorporating protection in high winds (e.g., JPACE block 2)
- **Transition into testing:** e.g., JSLIST NTA tests
- **Provide otherwise unavailable data:** validate IPE model simulations (input into JPM-IP modeling & simulation efforts)

Background

- **<u>Aerosol</u>**: Assembly of liquid or solid particles suspended in gaseous medium long enough to be observed or measured (~0.001 – 100 µm)
- **<u>Agglomerate</u>**: Group of particles bound together by van der Waals forces or surface tension
- **<u>Particle size</u>**: 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)

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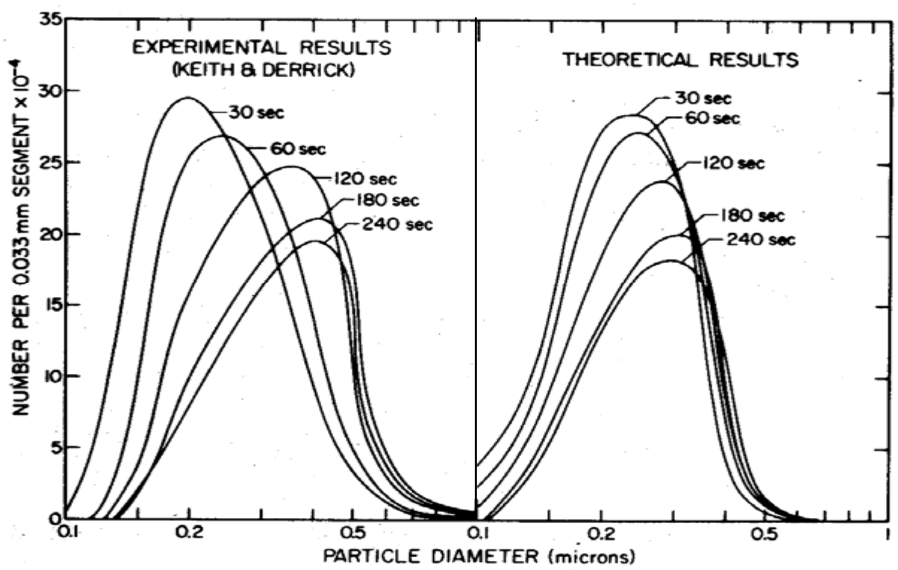
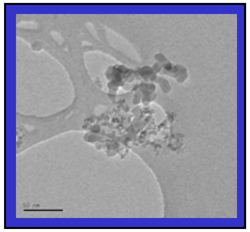
Change in mean particle size and number as a function of time



D1	D2	10 nm	100	1000	10,000
10 nm		67			
100		180	8.6		
1000		1700	24	3.5	
10,000		16000	220	10.3	3.0

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



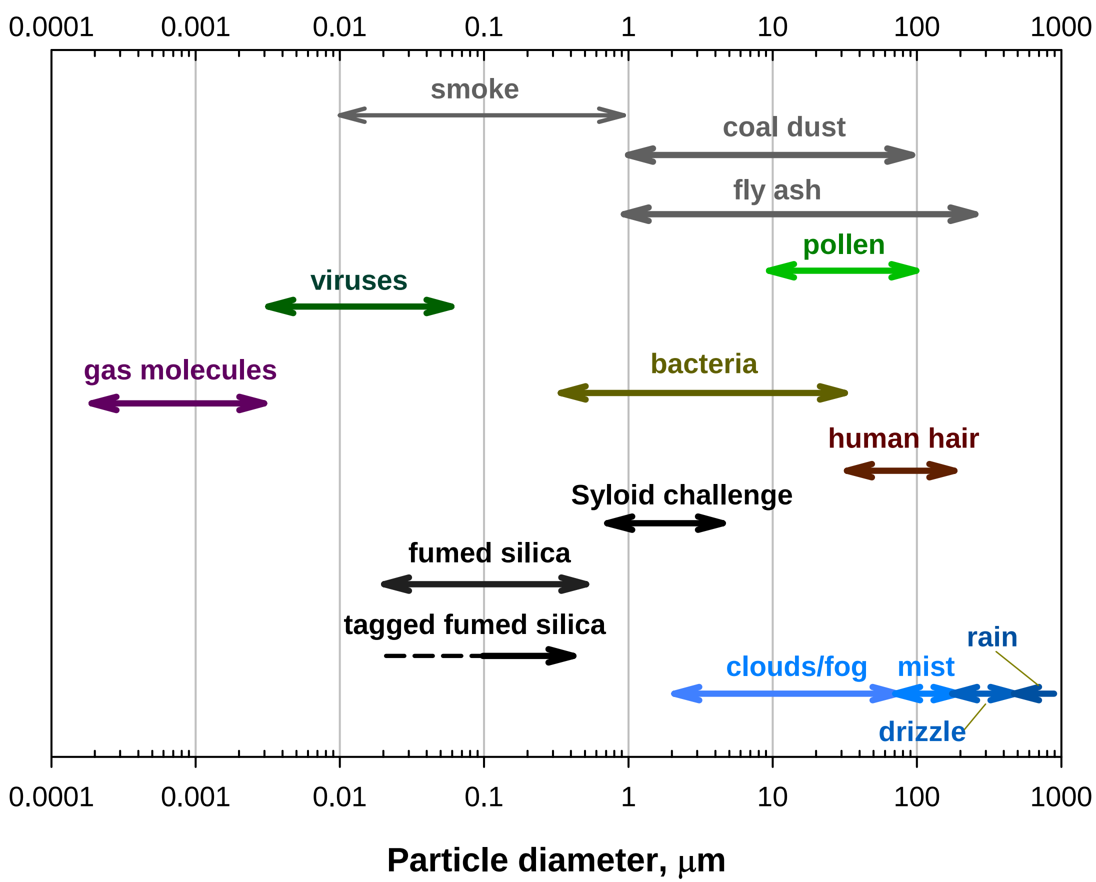
$$\frac{dN}{dt} = -KN^2$$

Smoluchowski (1917)

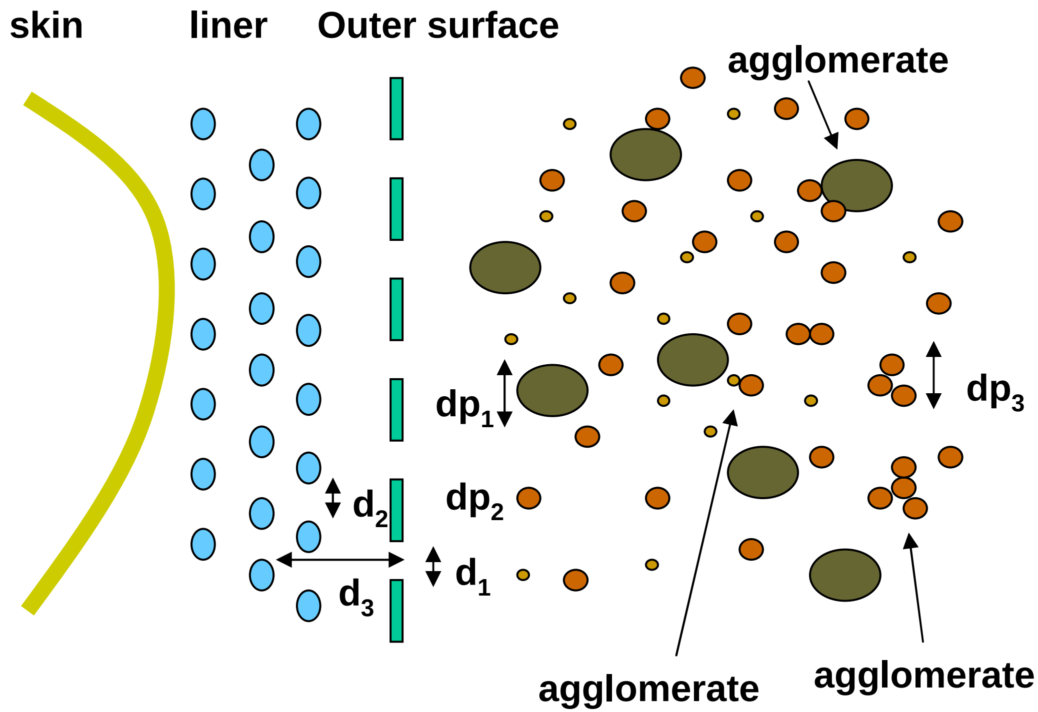
N = number
t = time
K = Coagulation coefficient

Background

Approximate sizes of representative natural and synthetic aerosols



Aerosol Penetration Mechanisms

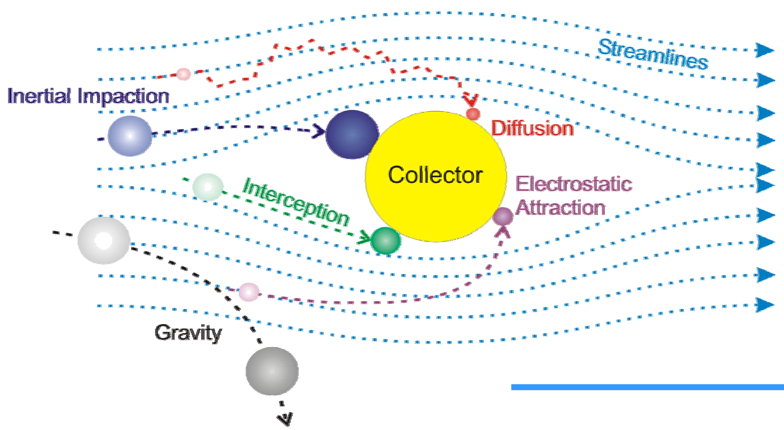


Driving forces:

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

Influencing factors

- particle inertia (m•v)
- dp_i/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, pulsitile 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

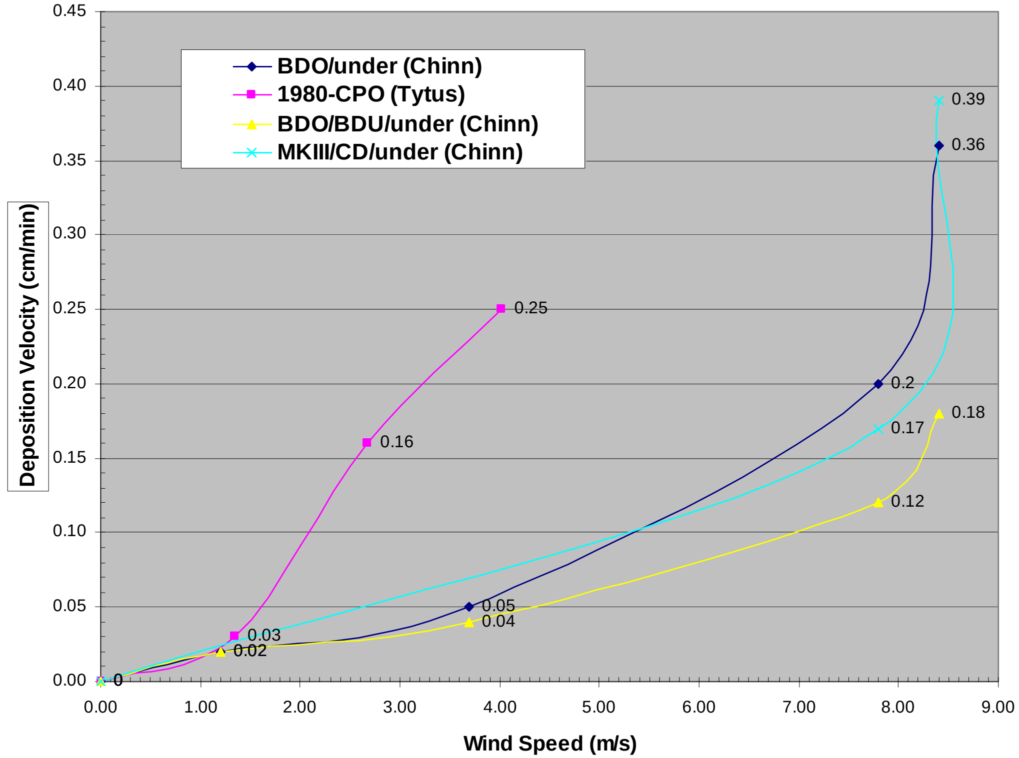
Aerosol Deposition

- < 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)

<u>Deposition Velocity</u> (V_d)

$$V_d = \frac{m_{deposited} - m_{background}}{A_{sample} \bullet C_m \bullet T}$$

M = aerosol mass
A = surface area
C_m = mass concentration
T = exposure time

1980-CPO: Chemical IPE ca.1980s
BDO/ BDU/under: Battledress overgarment over battledress uniform & underwear
BDO/under: BDO & underwear
MKIII/CD/under: Navy chemical IPE over chambray shirt, denim trousers & underwear. *Chinn (2004)*

DoD Project O49 elevated wind study

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

Block	Scenario	Configuration		Exposure Time (min)	Wind Speed (mph)	Trials
		Ensemble[a]	System Modification			
Block I	1	IPE	None	10	0 to 2	3
	2	IPE	None	10	10	3
	3	IPE	None	10	20	3
	4	IPE	None	10	~40	3
Block II	5	IPE	None	3	P+[b]	3
	6	IPE	Taped[c]	10	P-[d]	3
	7	IPE	Taped	10	P+	3
	8	IPE	Untaped, Poncho	10	P+	3
	9	IPE	Untaped, Rain Gear (Wet Weather)	10	P+	3
	10	IPE	Taped Rain Gear (Wet Weather)	10	P+	3
	11	IPE + BDU	None	10	P+	3
	12	IPE	None	30	P+	3
	13	IPE	None	10 chamber 20 clean room[e]	P+	3

[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

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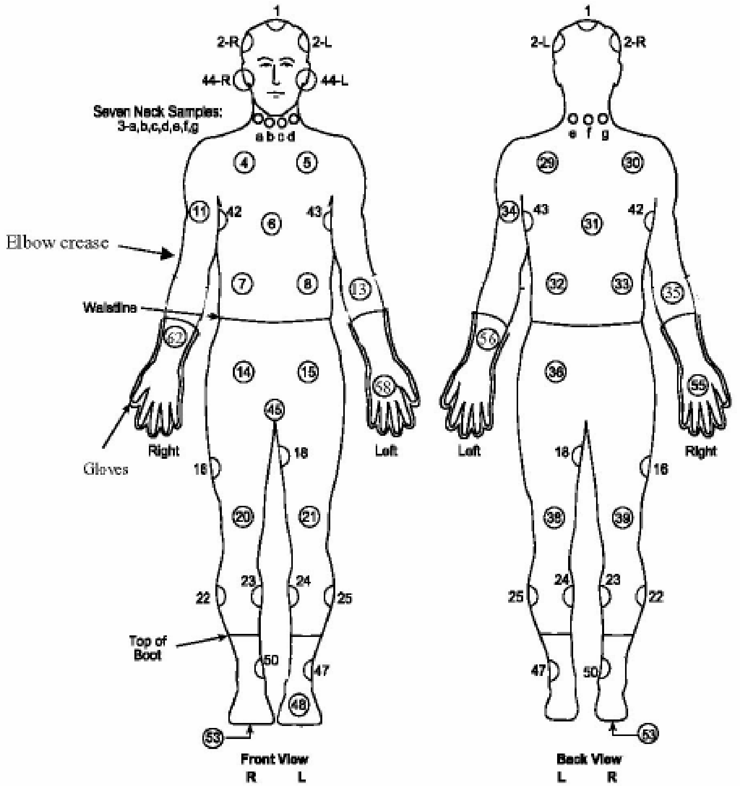
DO-49 study: Test conditions

	mean	SEM
Mass Median Diameter (mm)	2.72	0.08
Geometric Standard Deviation	2.52	0.09
Average mass concentration (mg/m^3)	188.1	8.2
CT (mg m^{-3} min)	1976.6	145.6
Average Temp (ºF)	74.3	0.7
Average RH (%)	43.4	1.1

<u>Wind Speed (mph)</u>

- 3
- 10
- 20
- 40

Environmental and simulant conditions



Skin & material sampling sites

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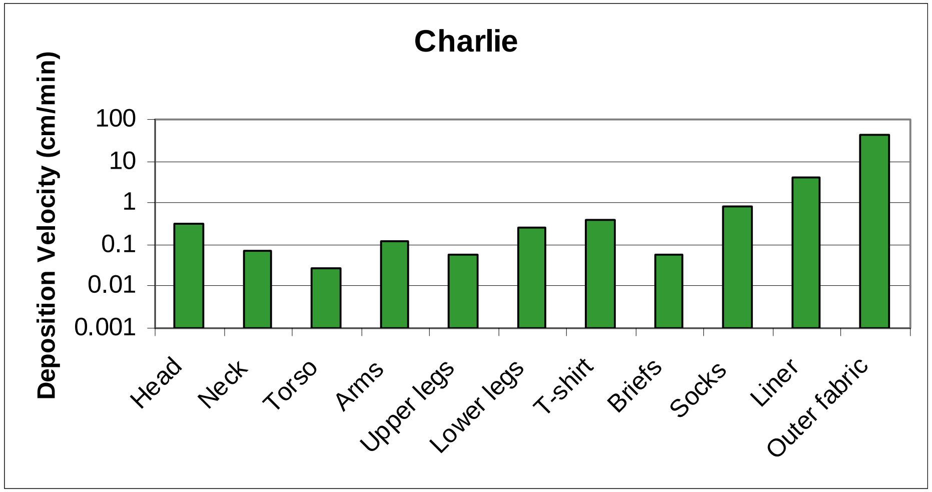
DO-49 elevated wind study:
Results of wind speed/garment combinations

Skin deposition of aerosol simulant: UV illumination of Fluorescent tag



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)***

Approach

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

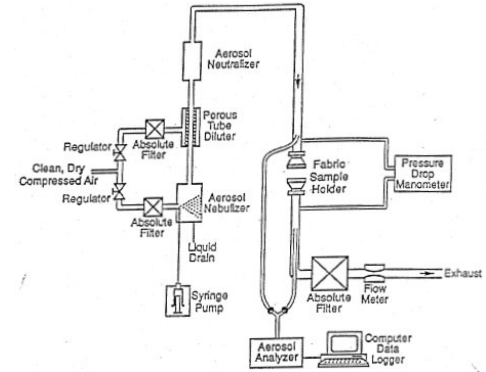
- particle size & size distribution
- tag distribution

• Swatch penetration (RTI)

- Liquid vs. solid phase aerosols (0.02 - 1.0µm)
- Variable pressure gradient (wind speed)

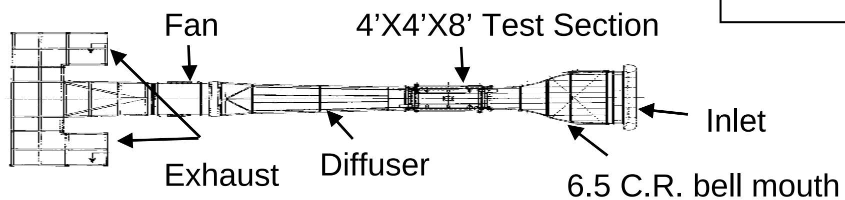
• Dissemination, wind tunnel

• Characterization, wind tunnel



RTI swatch test fixture: aerosol penetration in wind

NAVAIR wind tunnel



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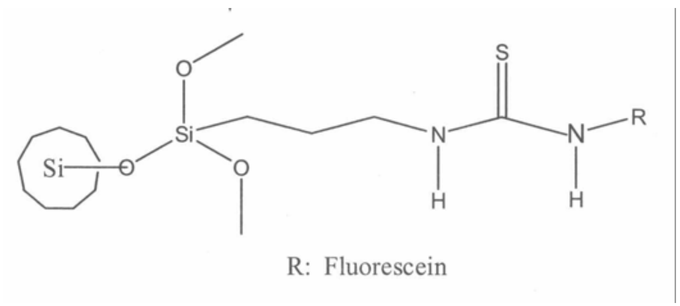
Effects of elevated wind speed on agent penetration of IPE

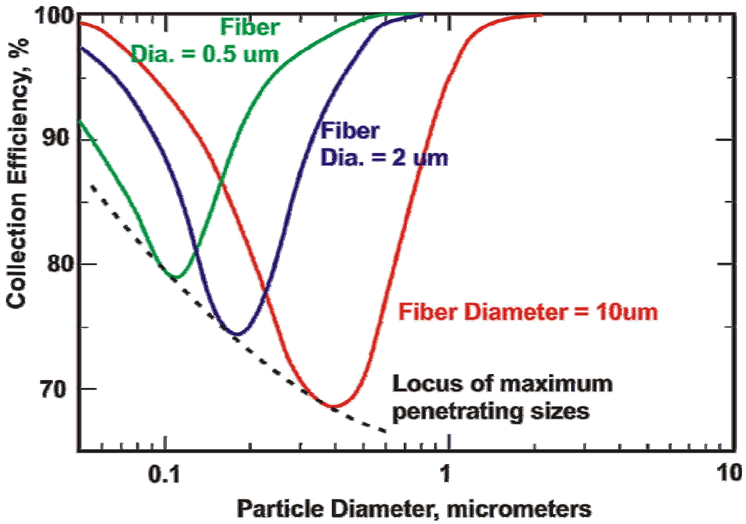
<u>Particle Tagging:</u> Understand particle surface chemistry regarding tag adsorption and agglomeration

- Covalent bonding of fluorescent material with fumed silica particle



<u>Filtration:</u> 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



Drawn from Hinds (1982)

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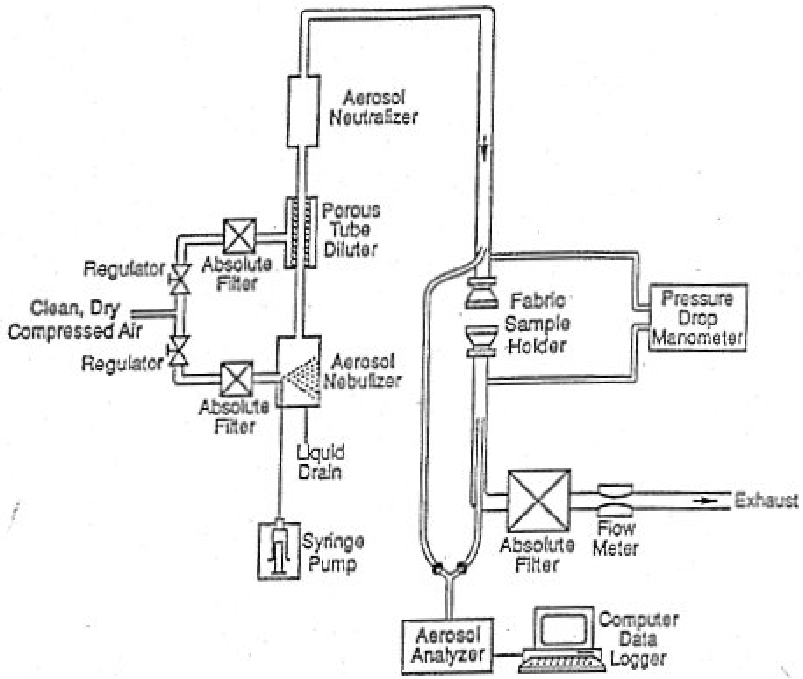
Effects of elevated wind speed on agent penetration of IPE



RTI swatch test fixture: aerosol penetration in wind

Swatch sample: outer shell & inner liner

Fabric Pressure Drop (" H2O)	Face Velocity (cm/s)	Wind Speed (mph)*
0.1	0.57 - 0.91	14
0.5	3.14	32
2	13.14	64

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*

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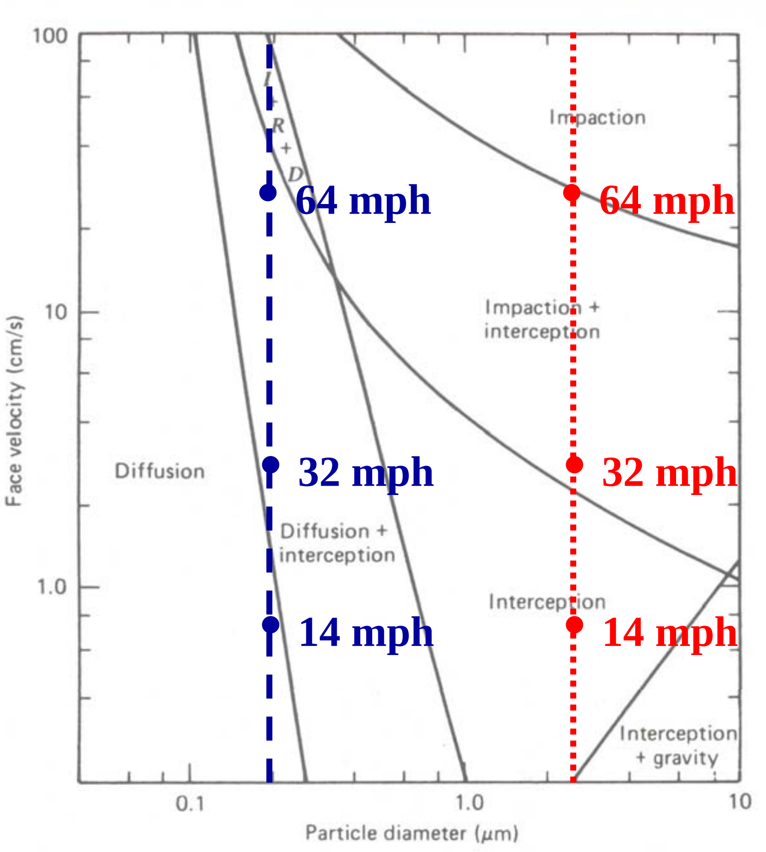
Effects of elevated wind speed on agent penetration of IPE

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

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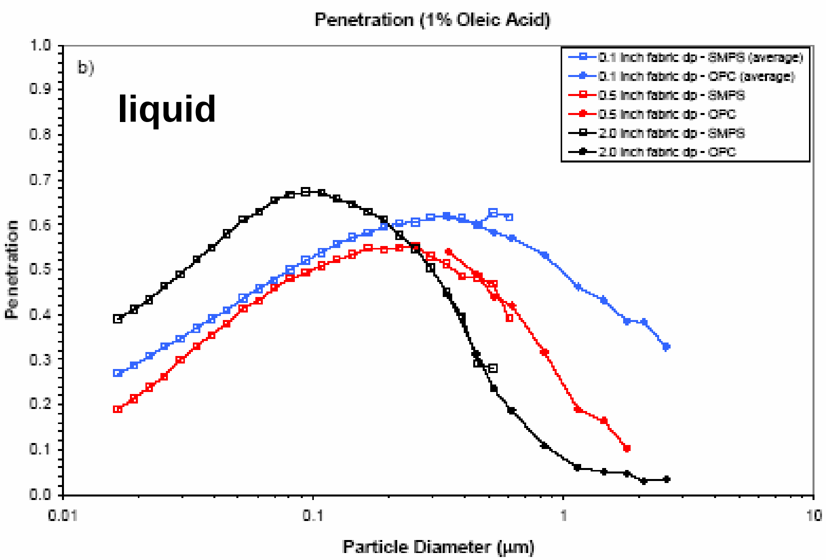
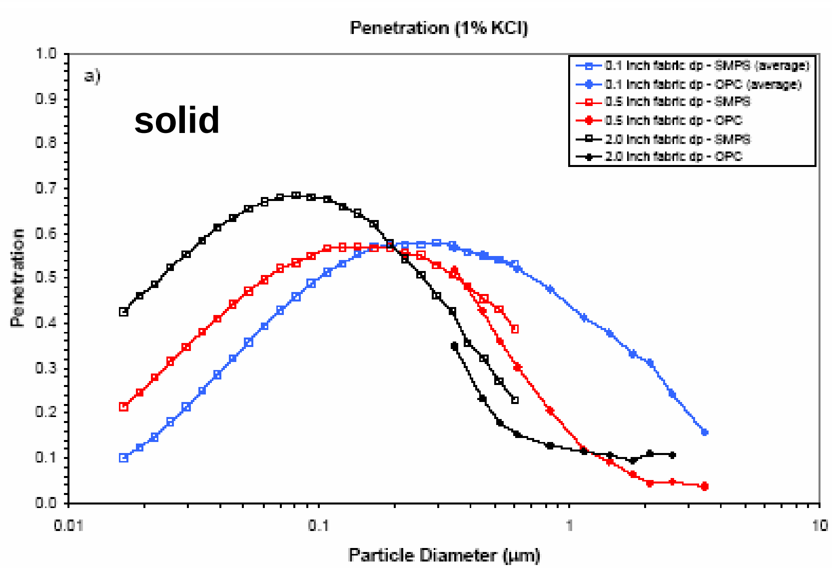
JSTO Elevated wind speed: Phase 1 results





Swatch penetration

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

$P_{obs}=C_{downstream}/C_{upstream}$

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

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JSTO Elevated wind speed: Phase 1 results

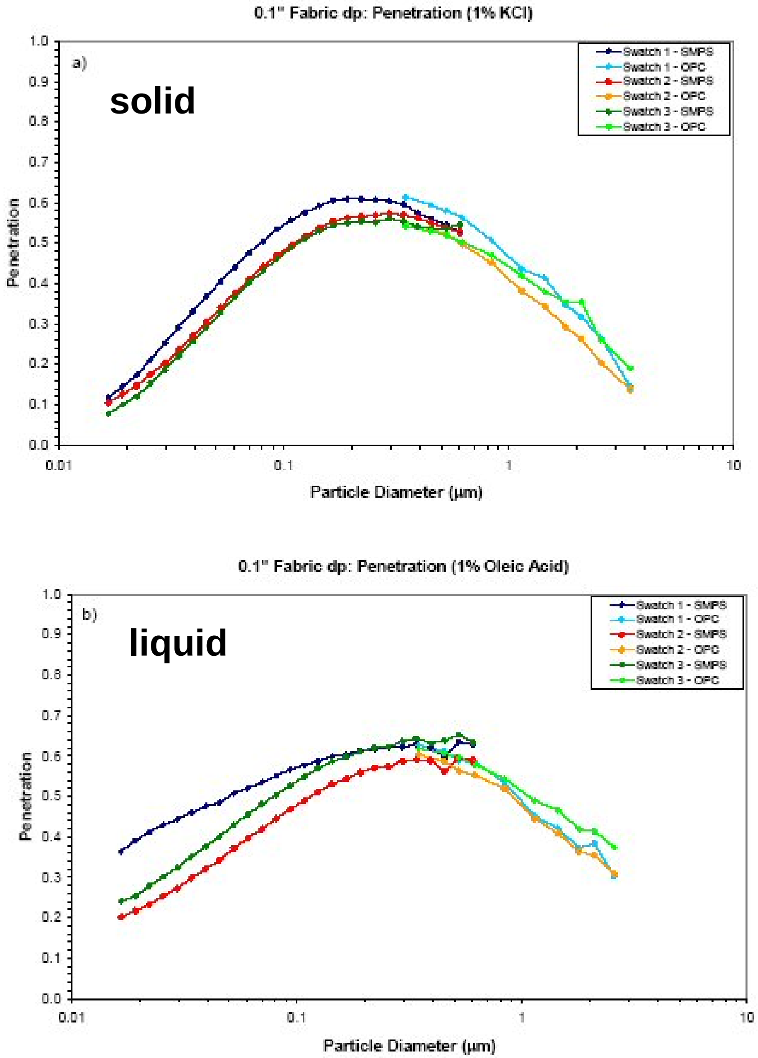

Figure 4. Penetration versus particle diameter for the triplicate fabric swatches at 0.1" fabric pressure drop with: a) KCl aerosol and b) oleic acid aerosol.

<u>Reproducibility</u>

Results from 3 independent trials at 0.1" pressure drop

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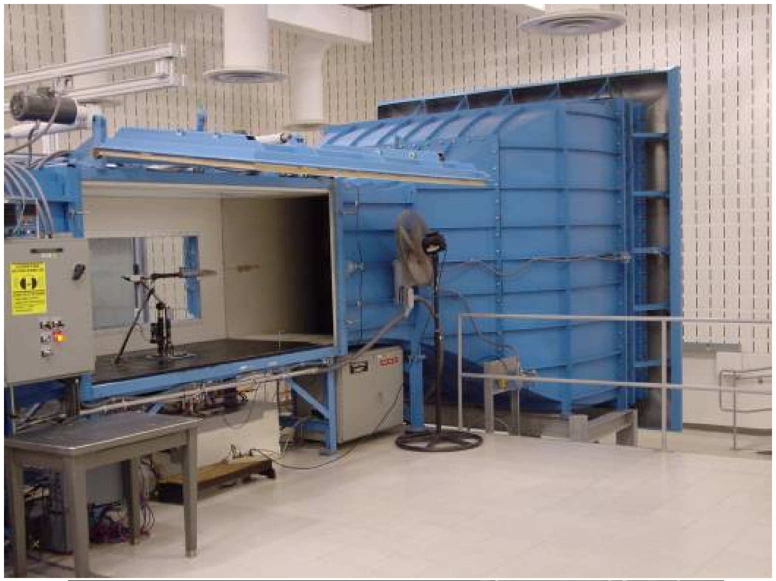
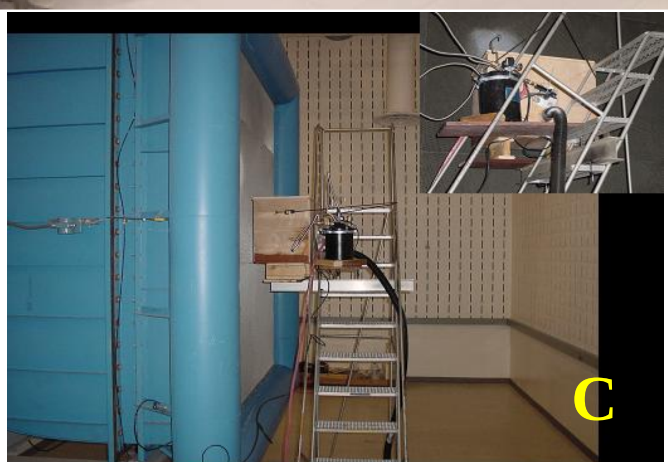
JSTO Elevated wind speed: Aerosol dispersion





<u>Prototype aerosol dissemination</u>

A - Spray system with Laskin nozzle

B - Dispersion box; *Inset: With top removed*

C - Dispersion System mounted in NATF

Inset: Rear of system

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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:

Literature Review:
Dr. Kenneth Chinn
Stephen Coleman
Teresa Kocher
Maura Rudy
Kathy Schaneveldt
Sponsor: JPACE

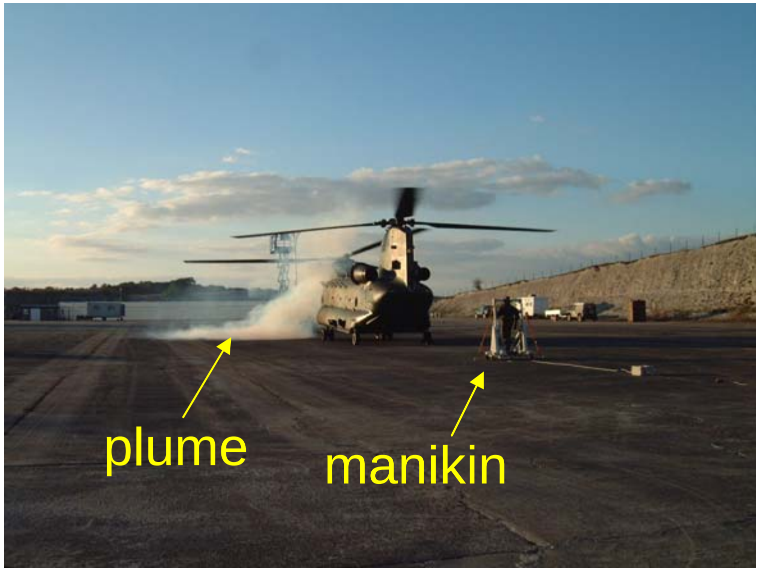
DO-49 study:
Jean Baker
James Hanzelka
Nathan Lee
Grant Price
Charlie Walker
Sponsor: JSIG

JSTO study:
Dr. Tom Cao
Terence Ghee
James Hanley
James Hanzelka
Dr. Chris Olson
Dr. Richard Phan
Sponsor: JSTO (Tony Ramey, CAPO)

Questions?

Backup slides

Rotorwash effects



Effect of wind & challenge dissemination
(DSTL 2002 study)

Literature Review

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

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