



Naval Surface Warfare Center, Dahlgren Division
CBR Analysis, Testing, and Systems Engineering Branch

BIOLOGICAL WARFARE AGENT SLURRY DROPLET METHODOLOGY

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Event Description

➤ Biological Warfare Agent Slurry Attack

❖ Commercial spraying system

- Crop duster
- Truck-mounted
- Backpack

❖ Exploding munition



Ayres Crop Duster



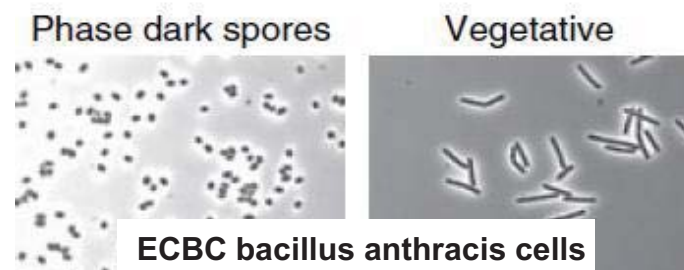
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Slurry Physical Properties

- **Bulk Density**
 - ❖ Density of aqueous slurry fill
 - ❖ 1.02 g/cm³ to 1.11 g/cm³
- **Particle Density**
 - ❖ Density of particle after evap.
 - ❖ 1.2 g/cm³ for spores and 1.1 g/cm³ for other organisms
- **Solid Mass Percent**
 - ❖ Percent of organisms, suspended solids, dissolved solids
 - ❖ 1% to 20% with ~4% typical as growth media
- **Agent Purity**
 - ❖ Percent of solids that is organisms
 - ❖ 80% to almost 100% for sophisticated state-run programs
- **Viability Decay Rates**
 - ❖ Exponential rate at which airborne organisms die
 - ❖ 1%/min to 10%/min in sunlight, 0%/min to 5%/min at night



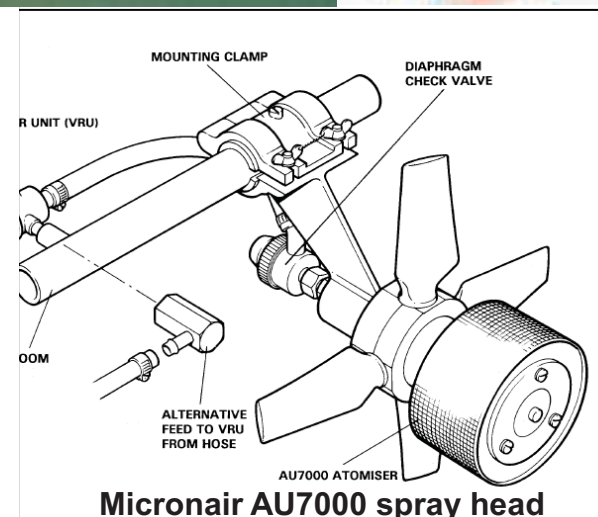


Droplet Size Distribution

- **Release Parameters**
 - ❖ Total release mass
 - ❖ Dissemination efficiency
 - ❖ Droplet mass-median dia. (MMD)
 - ❖ Geometric distribution sigma
- **Log-Normal Probability Distribution Function**

$$P = \frac{\exp[-(\ln D - \ln D_m)^2 / (2 \ln^2 \sigma_g)]}{[(2 \pi)^{1/2} \ln \sigma_g]}$$

- **Define 50 Droplet Size Bins (-3 to +4 σ_g)**
 - ❖ Compute total number of droplets
 $d_{NMD} = d_{MMD} \exp(-3 \ln^2 \sigma_g)$
 - ❖ Integrate error function for each bin
 - ❖ 10 mm maximum diameter
 - ❖ Combine sizes < 10 μm as respirable





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Transport and Diffusion

- **Source is a Gaussian Cloud or Plume**
 - ❖ Immediate droplet deceleration in planetary boundary layer
 - ❖ Concentration decreases away from cloud center or plume centerline
 - ❖ Gaussian distribution using cloud sigmas and initial location:
$$C = \exp[-(x - x_0)^2/2 \sigma_x^2] \exp[-(y - y_0)^2/2 \sigma_y^2] \exp[-(z - z_0)^2/2 \sigma_z^2] \\ \times m/[(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z]$$
- **Individual Droplet or Size Bin Transport and Diffusion is Independent of Approach**
 - ❖ Gaussian puff or plume
 - ❖ Lagrangian particle
 - ❖ Computational fluid dynamics
- **Should Include Inertial Diffusion Factor**
$$f_v = [1 + (5v_t/u)^2]^{-1/2}$$
 - ❖ Multiply by square of turbulence velocity





Droplet Fall

- **Terminal Velocity is Relevant at Altitudes Below ~15 km**
- **Algorithm Includes Droplet Deformation and Viscous Recirculation**
 - ❖ **Uses liquid surface tension and viscosity**
 - ❖ **Effects are not relevant for droplets < 1000 μm in diameter**
 - ❖ **Slurry droplets leading to respirable particles are < 100 μm in diameter**
- **Simpler Equations are Based on Reynolds Number, Air Properties, Slurry Density, and Droplet Diameter**
$$\text{Re} = (9/2)^2 \left(\{1 + (2/9)[4 g \rho_a (\rho_d - \rho_a) D^3 / (18 \mu_a^2)]^{1/2} \}^{1/2} - 1 \right)^2$$
$$v_t = \mu_a \text{Re} / (\rho_a D)$$
- **Terminal Velocity is Used to Track Droplet Height with Time**



Droplet Mass Balance

- **Function of Water Vapor Diffusivity, Droplet Diameter, Sherwood Number, Slurry Volatility, and Water Vapor Concentration**

$$\delta q / \delta t = \pi \vartheta D Sh (V - Rh V_b)$$

$$Sh = 2(1 + 0.276 Re^{1/2} Sc^{1/3}) \rightarrow \text{more complex for } D > 1000 \mu m$$

$$Sc = \mu_a / (\rho_a \vartheta)$$

$$\vartheta = \vartheta_0 (T/T_r)^{0.75} (\rho_r/\rho_a)$$

$$V = 10^{v1-v2/(v3+Td-273.15)} f_e W/RT_d$$

$$V_b = 10^{v1-v2/(v3+T-273.15)} W/RT$$

❖ V is at droplet temperature, and ϑ and V_b are at air temp.

- **Slurry Volatility is Adjusted for the Water Mass Fraction**

$$f_e = 3 f_w - 2$$

$$f_w = \max (q_w/q, 0.764) \rightarrow \text{minimum } f_e \text{ is } 0.292$$

❖ Slurry properties are based on a 1996 NSWCDD study of biological weapons slurry formulations



Droplet Energy Balance

- **Function of Droplet and Air Temps., Water Heat of Evap. and Heat Capacity, Nusselt Number, and Air Thermal Conductivity**

$$\delta T_d / \delta t = \delta q / \delta t (T_d - H/ca) - \pi K D Nu (T_d - T_a) / (q ca)$$

$$Nu = 2(1 + 0.276 Re^{1/2} Pr^{1/3}) \rightarrow \text{more complex for } D > 1000 \mu m$$

$$Pr = 0.71 \text{ for air}$$

- ❖ First term on right is for energy lost with evaporated mass
- ❖ Second term on right is for energy added through convection

- **Droplet Mass Equation**

$$q = \pi \rho_d D^3 / 6$$

- **Extent of Droplet Evaporation**

- ❖ Volatility reduction plateaus, but evaporation continues
- ❖ Evaporation stops if $V = Rh V_b$ due to temp. or composition
- ❖ Evaporation will continue if $T_d < T_a$ when droplet warms
- ❖ A moist (and larger) particle results if evaporation stops



Droplet and Particle Deposition

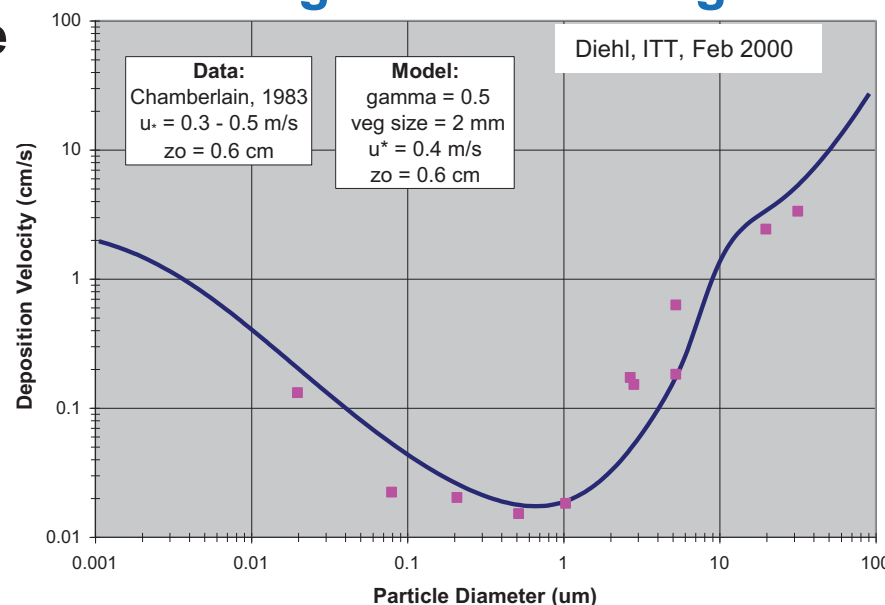
➤ Common Approach Uses Deposition Velocity

$$v_d = F/C$$

- ❖ 0.01 cm/s for 0.1 – 1 μm dia. and 1 cm/s for 10 μm dia.
- ❖ Plus: Considerable research done and data generated
- ❖ Minus: Concentration is reduced throughout cloud height

➤ NSWCDD Approach Uses Rate of Diffusion at Ground

- ❖ Flux and concentration give equivalent v_d
- ❖ Compute v_d for a range of environmental conditions
- ❖ Scale to match data
- ❖ 97% reflection for 0.1 μm
- ❖ 0% reflection for 10 μm
- ❖ Plus: Mass removed and reflected at cloud bottom
- ❖ Minus: Accurate for a limited range of conditions





Conclusions

- **NSWCDD has developed and implemented methodology which simulates the physical processes relevant to biological warfare agent slurry droplets generated from an attack.**
- **Release mass is divided into droplet size bins.**
- **The terminal velocity for each droplet size is tracked with time.**
- **The rate of evaporation of water from the droplet uses mass and energy balances and a volatility adjustment for composition.**
- **A fraction of slurry droplets and solid particles will deposit.**
- **More data are needed to better characterize the effects of temperature and slurry composition on vapor pressure.**
- **The slurry droplet methodology is appropriate for use with common atmospheric transport and diffusion methodology.**



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Thank You for Listening

Questions?