AP1000 Slides for Aerosol

Plugging & Behavior in Containment Leak Paths

Docket No: 52-006

Date: August 13, 2008

Aerosol Plugging & Behavior in Containment Leak Paths

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Design Basis Leakage

- A Defense-in-Depth measure
  - What measures and barriers provide protection to public health and safety if we have been wrong about success of plant response to events
- Selected leakage (~0.1% per day for AP1000) is an expedient
  - Quite difficult to prove leakage is less
  - Not conservative
    - Testing not done with temperatures or gases of accidents
    - On average 5 years since last testing
  - Mechanistic analysis of leakage requires information at levels of resolution below that of current containment codes

Aerosol Behavior in Leakage

- **Has not been addressed in design basis space in the past**
  - **Taking DF = 5 is equivalent to reducing leakage to 0.02% per day**
- **Has been an issue in severe accident analysis**
  - **Also involves mechanistic analysis of leakage**
- **Mechanistic analysis of aerosol behavior in leakage invites mechanistic analysis of the magnitude of leakage**
  - **Tests show this could be challenging**

Japan Containment Test

- Aerosol leakage thru 5 low-voltage and one high-voltage electrical penetrations and two types of hatch flanges and gaskets
  - Leakage evolved in time and depended very much on temperature

Deposition Mechanisms

- **Gravitational**
  - Always operational on earth
- **Diffusion**
  - Always operational but efficient only for very small particles
- **Turbulent**
  - Characterized by particle relaxation time
- **Inertial impaction**
  - Characterized by Stokes number
- **Phoretic**
  - Depend on gradients in temperature, concentration etc.
  - High velocity gas flow through leaks eliminates gradients in temperature quickly

What is a Stokes Number?

- **Consider a particle falling under the influence of gravity**

$$(\pi/6)D_p^3(\rho_m - \rho_g)g = 3\pi\mu D_p\chi\, V_{settling}/C_{slip} = V_{settling}/B$$

D_p = particle diameter

ρ_m = particle material density

ρ_g = gas density

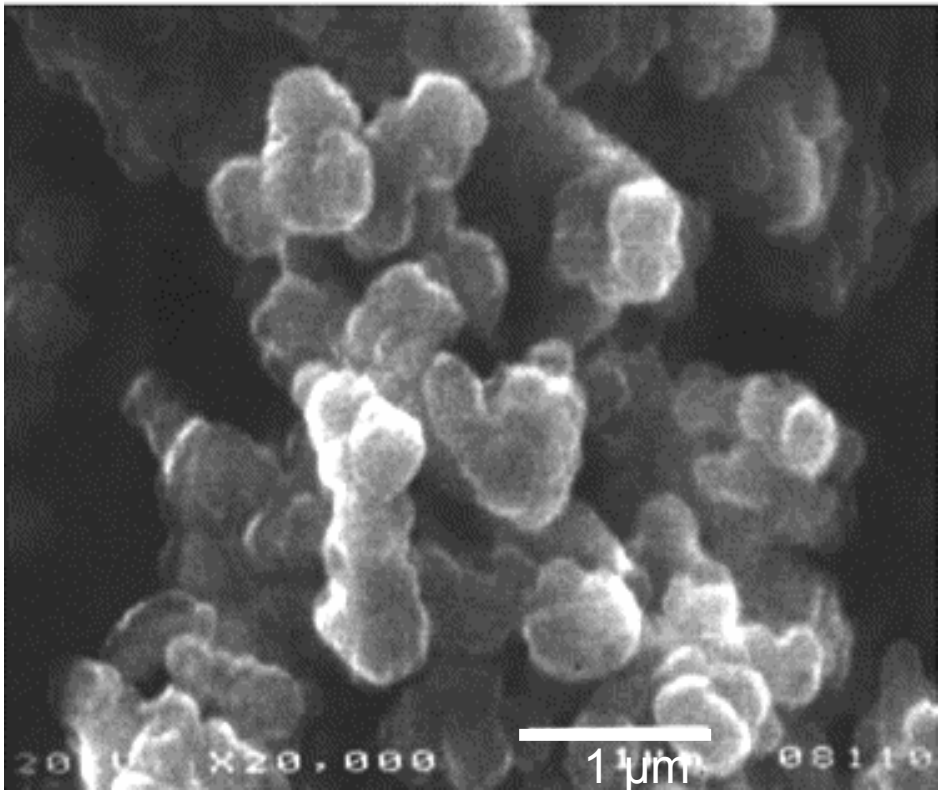
χ = shape factor (corrects for particles not being spheres and not being fully dense) always > 1

$V_{settling}$ = particle settling velocity

B = particle mobility

C_{slip} = slip correction factor (important only for for very small particles)

Particles observed in Phebus Tests

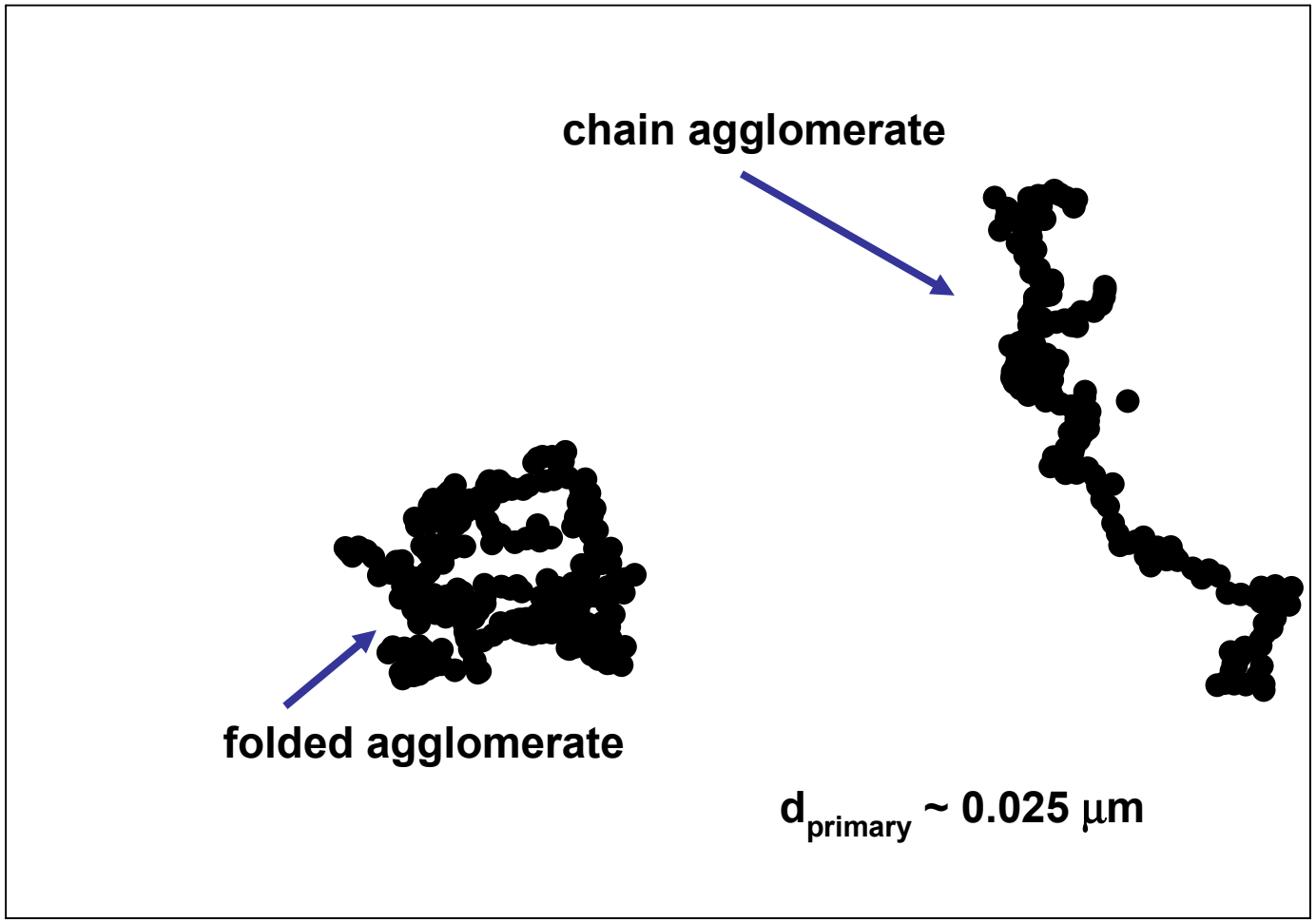


Aerosols expected in reactor accidents are not fully dense spheres

Compositions of Aerosols from PHÉBUS Test

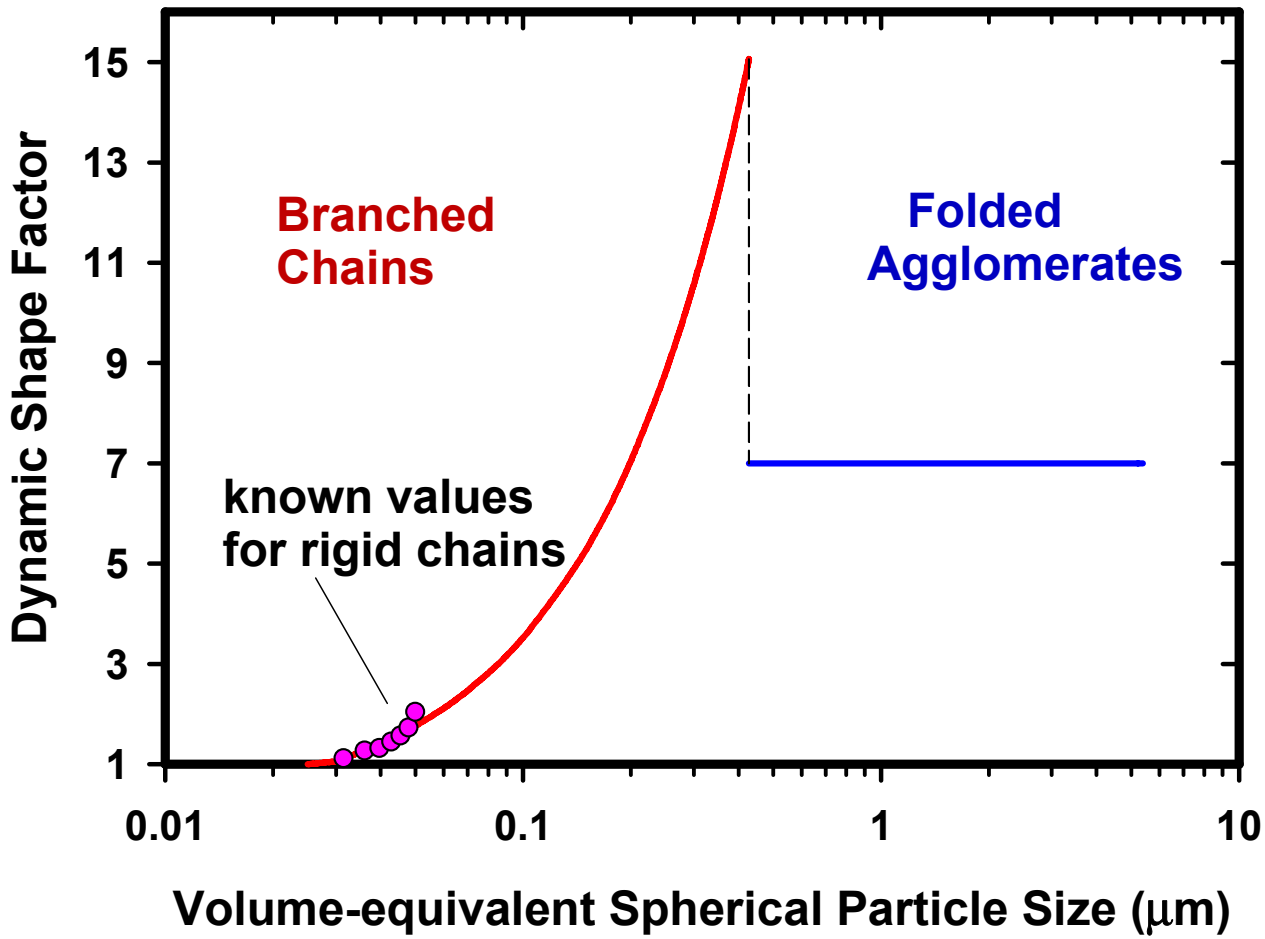
	Elemental Composition (weight %)							
Sample	Ag	In	Cd	Sn	U	Mo	Cs	other
11051	32	22	9	8	0	4	9	6
13810	30	8	3	8	6	17	24	3
16473	52	3	0	3	27	5	3	6
17034	46	10	4	6	13	8	6	8

AP1000 assumes particles are fully dense CsI


chain agglomerate
folded agglomerate
$d_{primary}$ ~ 0.025 μm

Dynamic Shape Factor as a Function of Particle Size

Dprimary = 0.025 μm Fractal dimension = 1.78



Aerosol Settling Velocities

- For the fully dense, $\rho_m = 4\ g/cm^3$ particles assumed by AP1000 ($\chi = 1$):
- Realistic shape factors reduce settling velocities

Particle diameter (μm)	$V_{settling}$ (cm/s)
0.5	0.003
1.0	0.012
2.0	0.05
4.0	0.2
10	1.2

Stokes Number, cont'd

- **Particle mobility:**

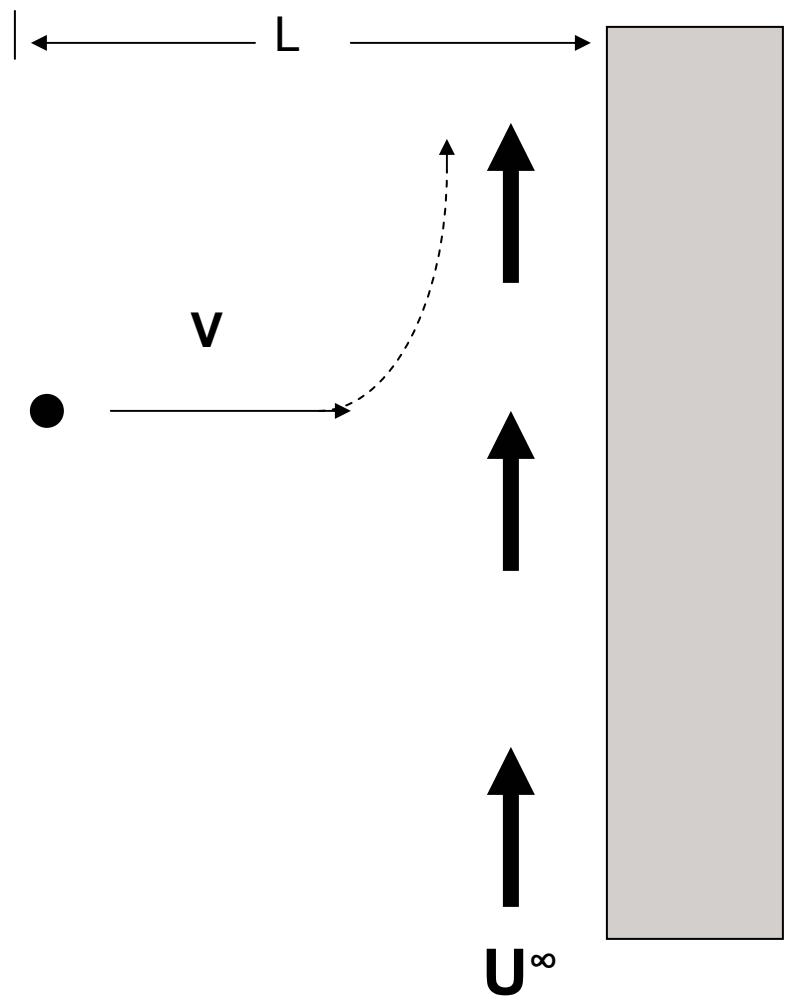
$$B = C_{slip} / 3\pi\mu D_p \chi \sim 1 / 3\pi\mu D_p \chi$$

- **Particle diffusion coefficient:**

$$D = kTB = C_{slip} kT / 3\pi\mu D_p \chi$$

Stokes Number, cont'd

- Consider a particle approaching a wall with gas flow across the wall
- Will the particle hit the wall?



Stokes Number, cont'd

$$(\pi/6)D_p^3\rho_m \, dV/dt = (U^\infty - V) / B$$

Or

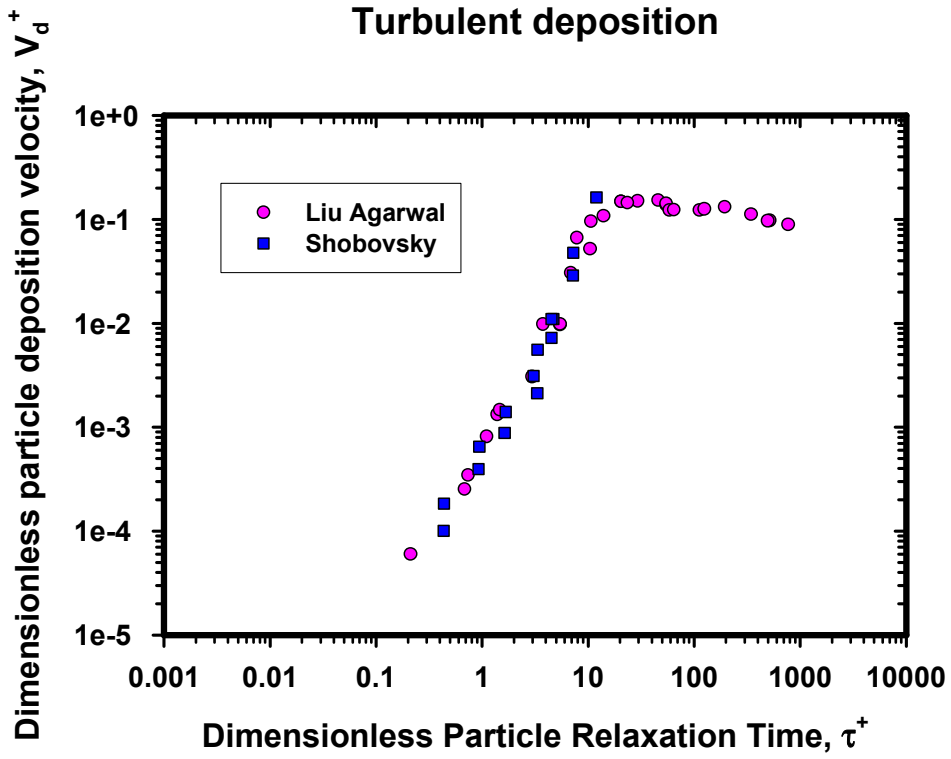
$$(1/(U^\infty - V)) \, dV/dt = 1/\tau_p$$

Tp = particle relaxation time = $\rho_m D_p^2 \, C_{slip}/18\mu\chi$

Used in the correlation of turbulent deposition along with eddy lifetime: $t^+ = \tau_p / \tau_{eddy}$

Turbulent Flow

- Turbulent deposition is an important deposition mechanism not present under laminar conditions
- Not obvious that 1.5 mm diameter leak a conservative bound suitable for analysis



Stokes Number, concluded

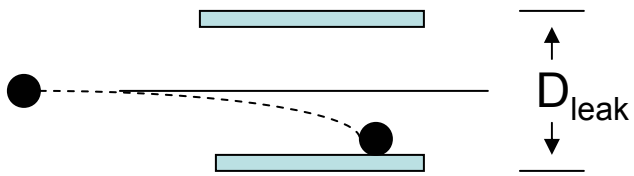
- **Particle "stopping" distance**

  $$\text{Stopping distance} = \tau_p U^\infty$$

- **Stokes Number:**

  $$Stk = \tau_p U^\infty / L = 2 \tau_p U^\infty / D_{leak}$$

  $$= \rho_m D_p^2 C_{slip} U^\infty / 9\mu\chi D_{leak}$$



Dimensionless number used to correlate deposition by inertial impaction of particles

- small numbers mean particles respond quickly to flow and resist deposition
- AP1000 ignores shape factors so Stk largest possible for assumed particle size

Deposition in Leaks Well Known to Aerosol Community

- **Sampling aerosol from a volume into size characterization equipment**
  - Sample must be representative of what is in volume
  - Avoid size preferential inertial impaction on outside or inside of tube by settling or inertial impaction
- **Davies criteria for "perfect" sampling**
  - Two important parameters

$$V_{settling}/V_{sampling} < 0.04$$

$$Stk < 0.032$$

- **Agarwal and Liu criteria for "pretty good" sampling**
  - For 90% sampling efficiency

$$Stk\ V_{settling}/V_{sampling} < 0.1$$

AP1000 only considers Stokes number

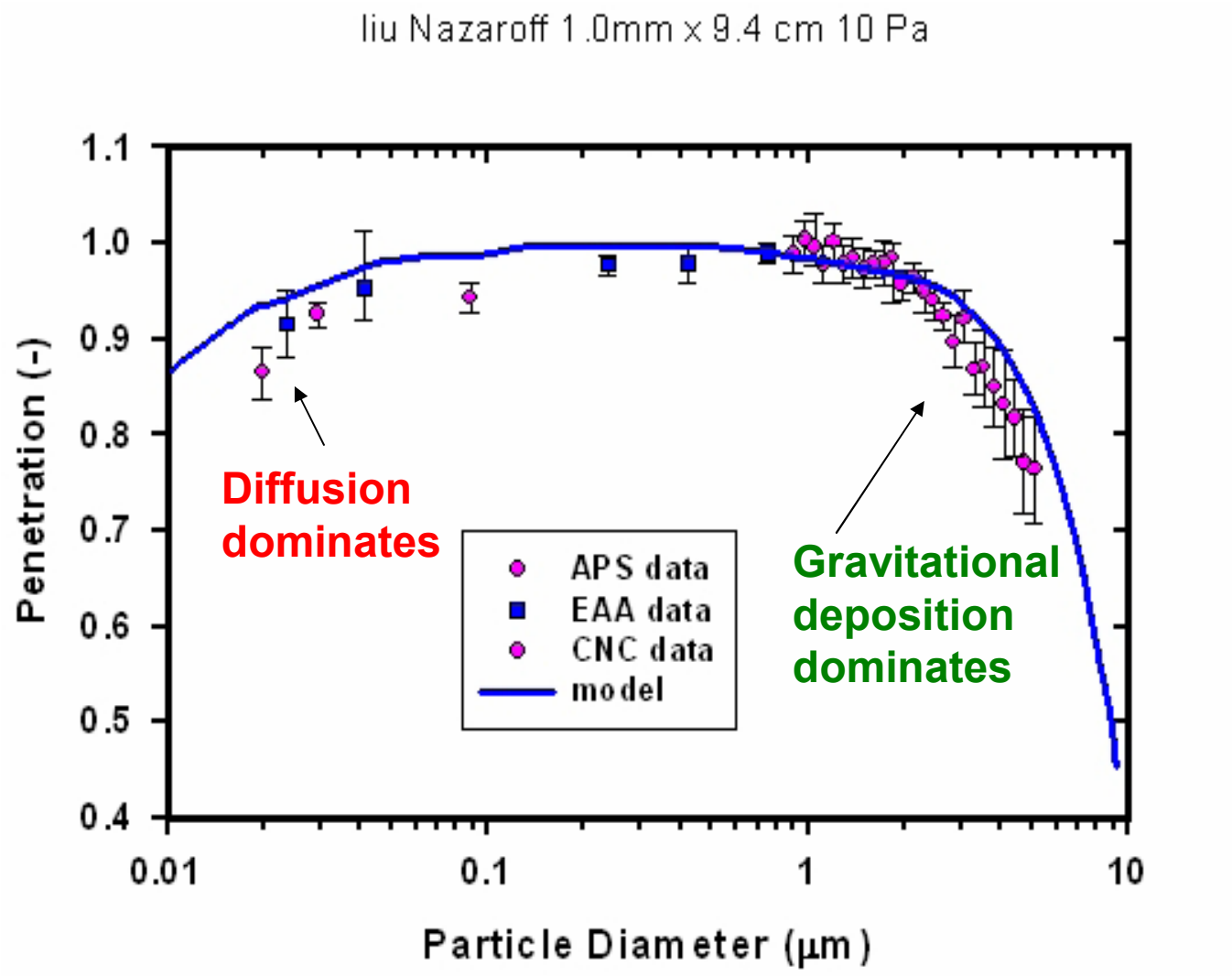
AP1000 Leak

- **Hypothesized leaks**
  - Cracks in welds
  - Degraded gaskets
- **Representative Leak**
  - 1.5 mm cylindrical hole 4.45 cm long
  - Reynolds number ~ 33400
  - Highly turbulent flow
  - Deposition for Stk > 1.5
  - Sonic gas velocities in leak ~ 330 m/s ($V_{settling}$ / $V_{sampling}$ < $1x10^{-5}$)

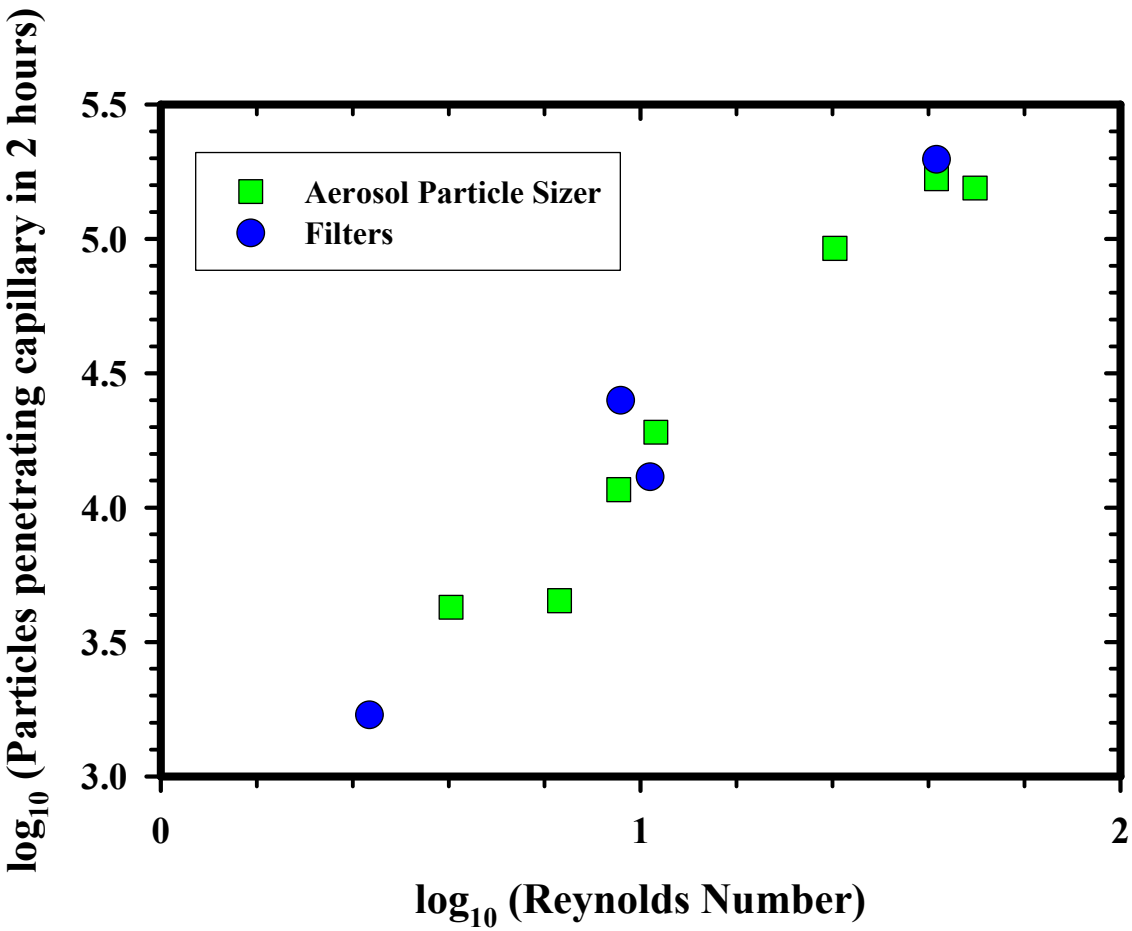
Is the representative leak bounding with respect to aerosol deposition ?

- **Probably not**
  - Laminar flow leads to particle deposition only by gravitational settling and diffusion
  - Turbulent flow augments this with turbulent deposition

Laminar flow conditions



In the laminar flow regime, there is less opportunity for deposition at higher Reynolds numbers (Mitchell & coworkers)



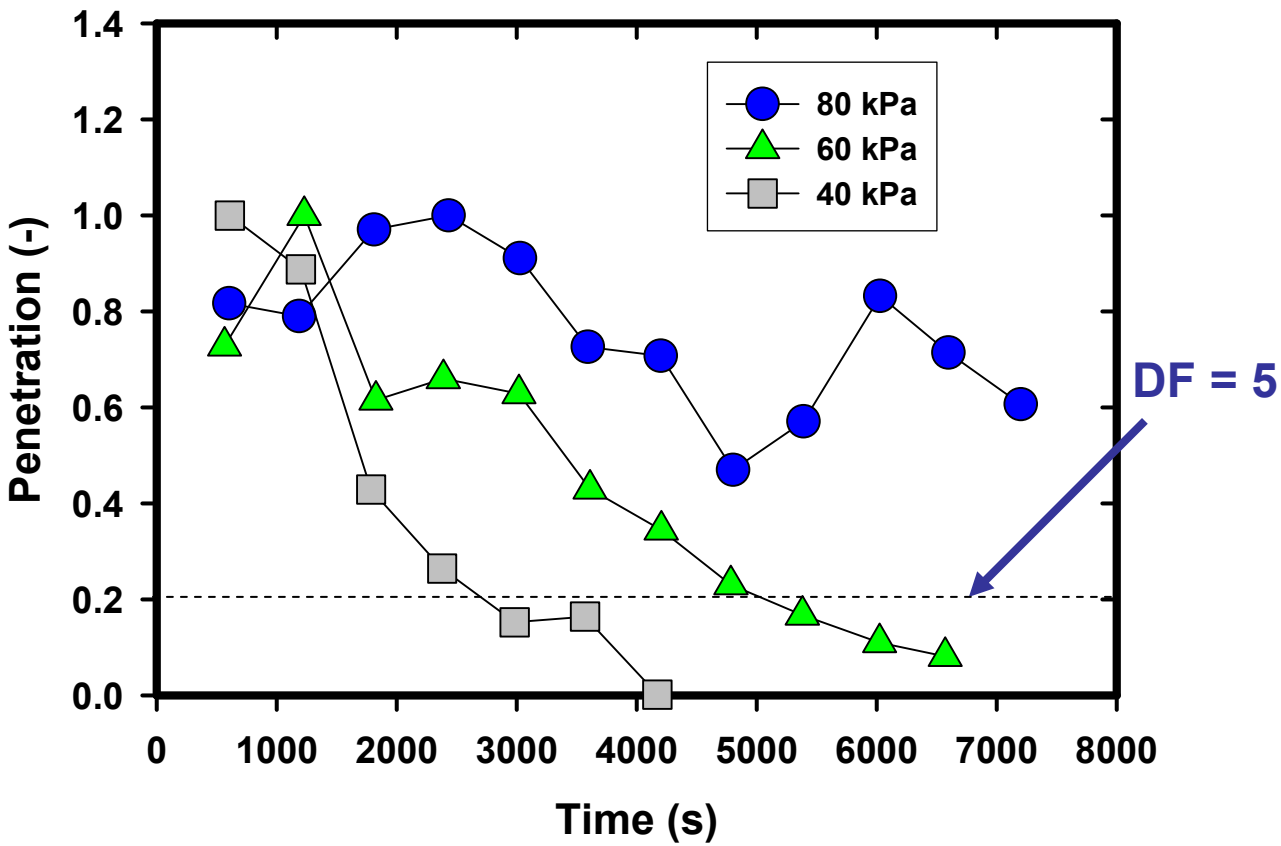
Even for very fine particles at low differential pressures it takes a long time to reach DF = 5 (Mitchell & coworkers)

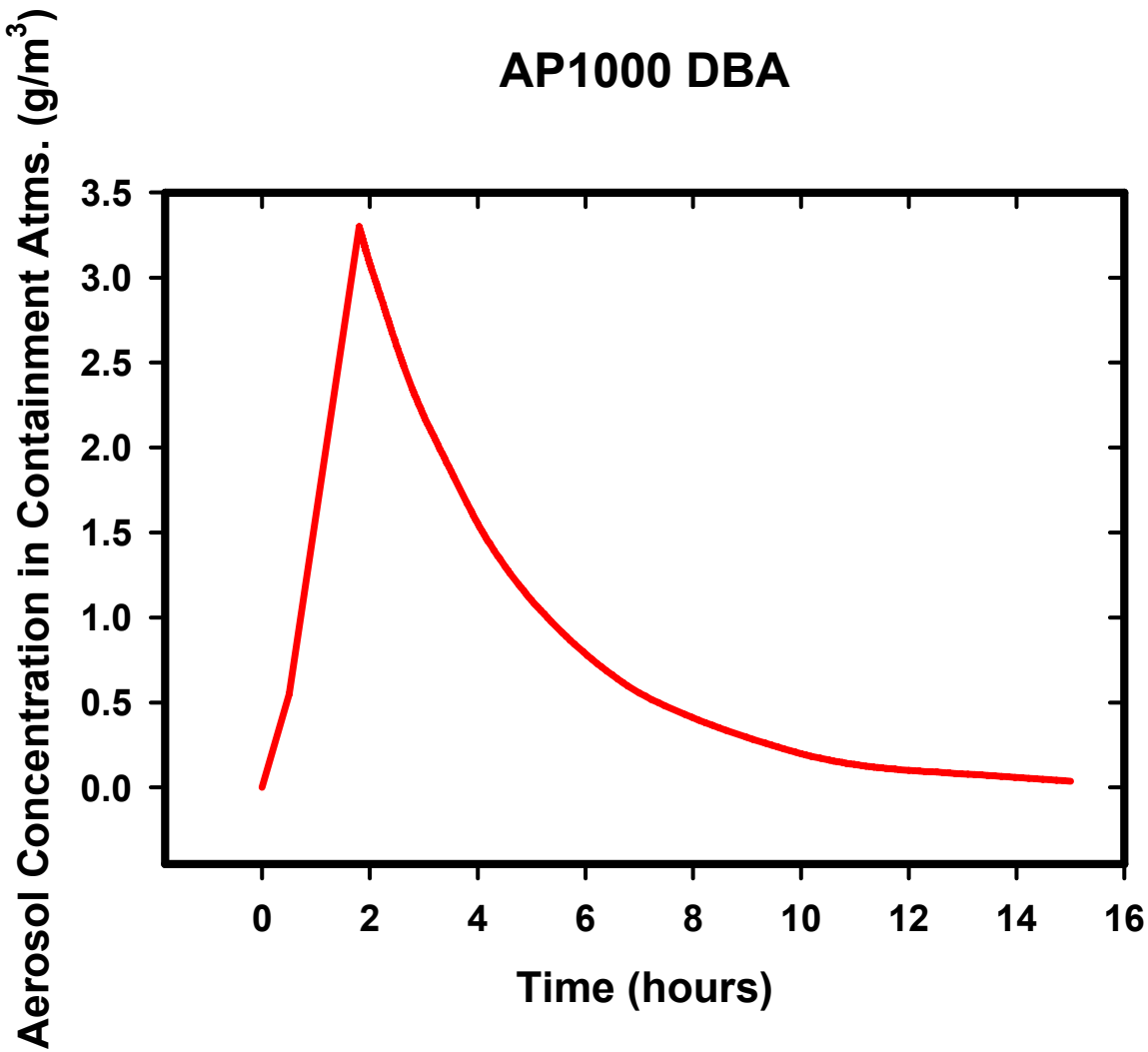
Note: ΔP for AP1000 analyses is greater than 80 kPa

Penetration through 30 μm x 20 mm capillaries

It takes time to plug

Aerosol concentration is high early in scenario




AP1000 DBA
Aerosol Concentration in Containment Atms. (g/m3)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
Time (hours)

Bounding Leak

- A set of fine capillaries (~90 μm) with laminar flow might be a more justifiable bound on the leak than one large hole with turbulent flow

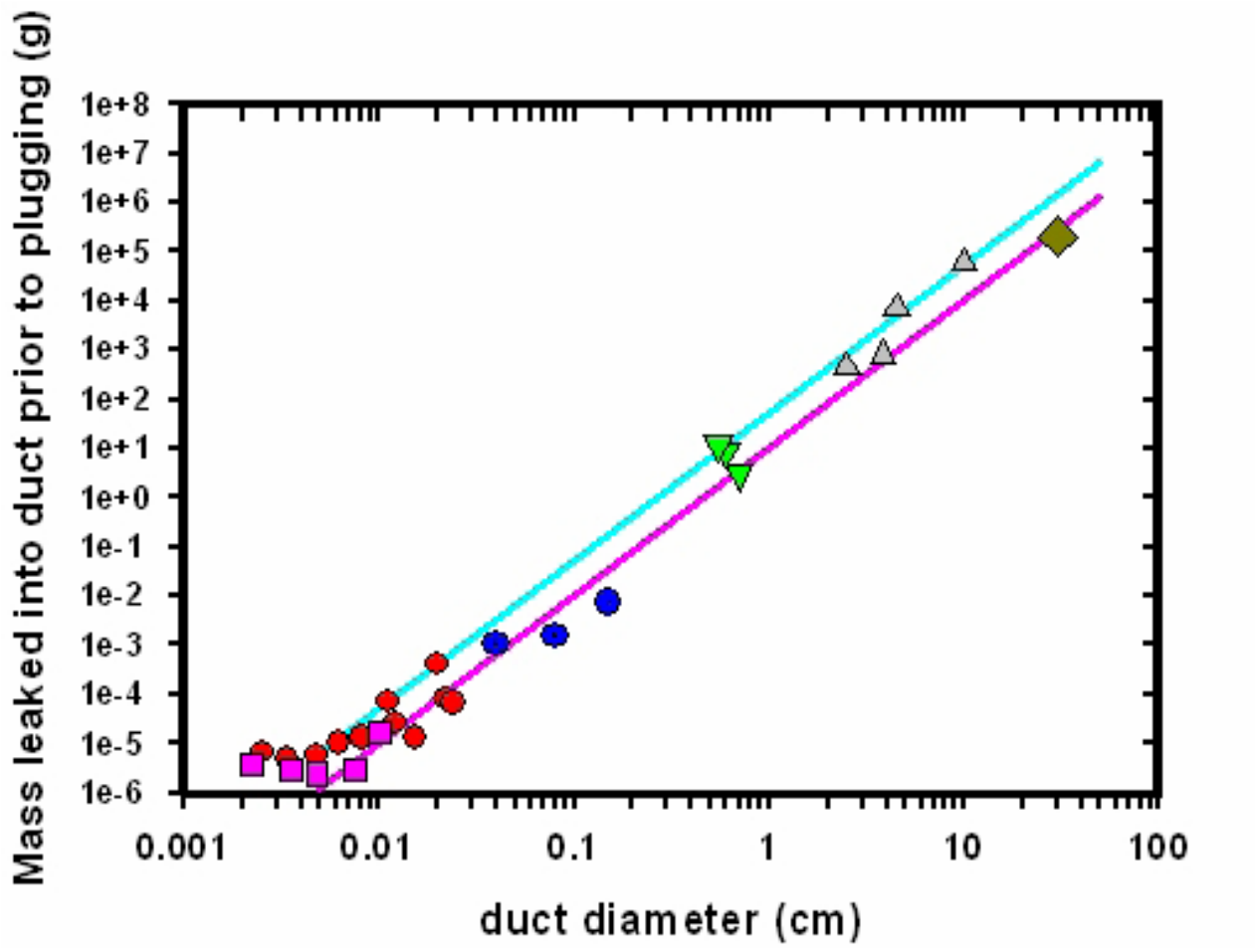
AP 1000 Invokes Morowitz Plugging Correlation

- Correlation developed for aerosol produced in sodium fires:

$$M_{leaked} = k\ D_{leak}^{3}$$

- Most experiments involved high concentrations and large particles
- Most experiments involved particle deposition by mechanisms other than inertial impaction
- Novick showed that for plugging to occur the Davies criteria for “perfect” sampling had to be violated

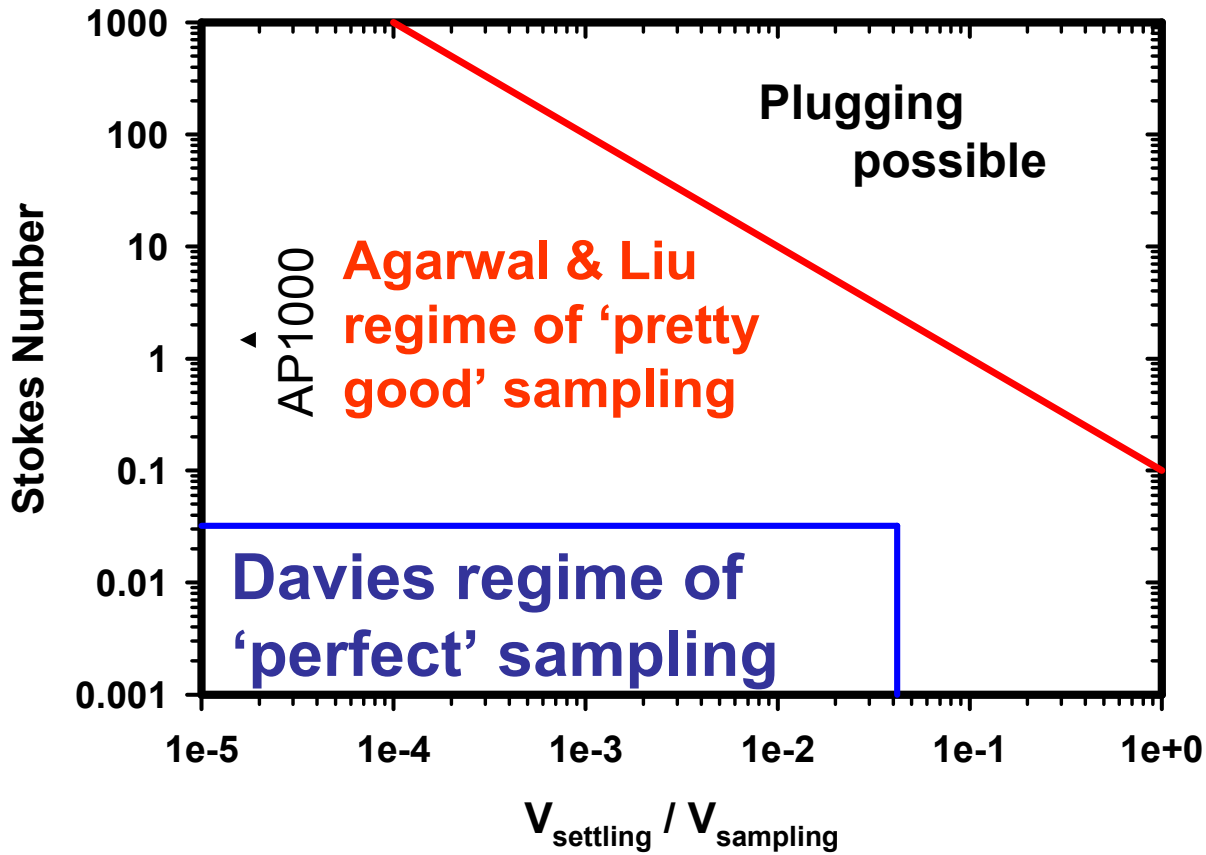
Morowitz Correlation

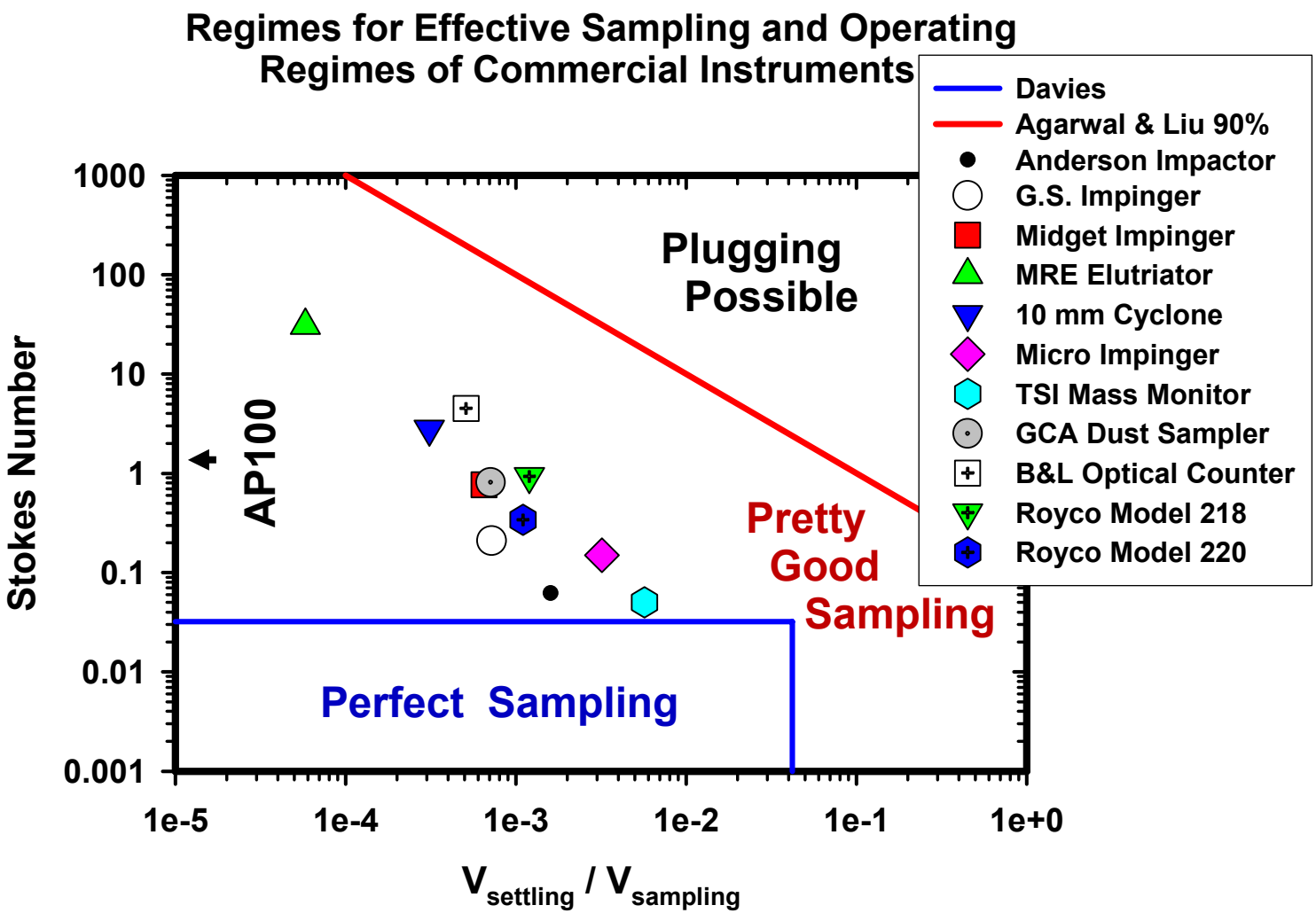


Examples of Data Used for Morowitz Correlation

Aerosol	Peak Concentration (g/m^3)	ΔP (bar)	Duct diameter (cm)
Na_2O_x + Na_2CO_3	15 -20	1.36	0.635
Na_2O_x	200 – 300	0.068	0.635
UO_2	900	~0.5	0.635
UO_2	230	0.5	0.635
Na_2CO_3	1.3 – 1.7	0.029-0.068	0.04 – 0.110
NaOH + Na_2CO_3	20	-	26.5

Regimes for Effective Sampling that Avoids Deposition on the Sampler Inlet

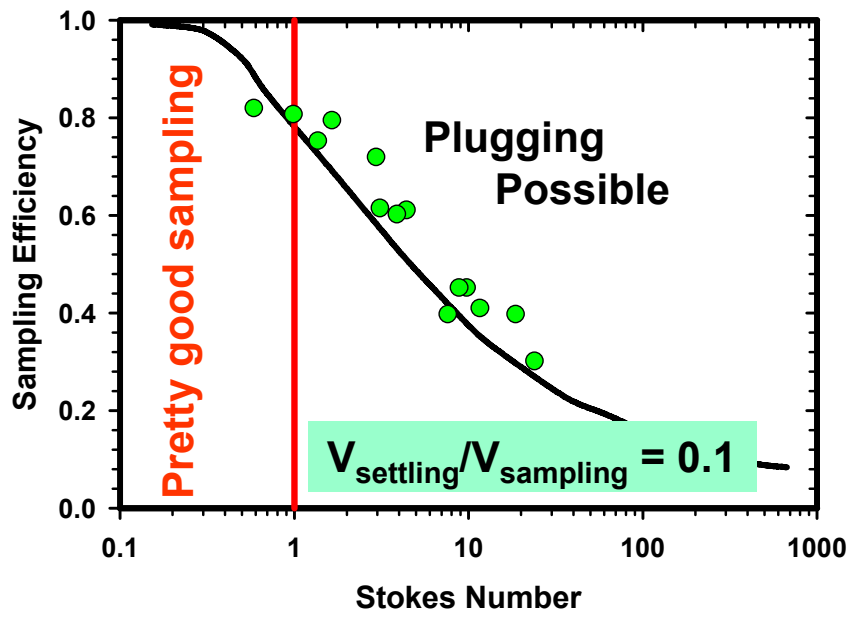



Regimes for Effective Sampling and Operating
Regimes of Commercial Instruments
Davies
Agarwal & Liu 90%
Anderson Impactor
G.S. Impinger
Midget Impinger
MRE Elutriator
10 mm Cyclone
Micro Impinger
TSI Mass Monitor
GCA Dust Sampler
B&L Optical Counter
Royco Model 218
Royco Model 220
Plugging
Possible
Pretty
Good
Sampling
Perfect Sampling
AP100
Stokes Number
1000
100
10
1
0.1
0.01
0.001
1e-5
1e-4
1e-3
1e-2
1e-1
1e+0
V settling / V sampling

Deposition Regimes

- **Agrawal and Liu analyses have endured the test of time**
  - **Other analyses (see Dunnet *et al.*)**
  - **Comparison to data (See Yoshida *et al.*)**

Data Compared to Analysis Results by Agrawal and Liu



Suppose that we assume particles do impact the walls

- **Is the requested DF consistent with data for similar situations?**
  - **flow path does not plug**
  - **But flow path does decontaminate gas stream**
- **Will particles bounce off surfaces they strike?**
- **Will deposited particles resuspend from surfaces into the flow?**

Data cited by Morewitz

- **Tubes that do not plug but do involve particle retention**
- **It is not apparent that DF = 5 is an appropriately conservative description of these data.**

Test	Re	D_{pipe}	DF
Fr57	7450	**0.54**	**1.003**
	14600	**0.54**	**1.1**
Se63	6000	**2.93**	**1.08**
	40000	**2.93**	**3.7**
	1600 to 14000	**7.14**	**1.06**
Fi62	3800	**1.02**	**1.09**
	9900	**1.02**	**6.6**
	7.8	**0.8**	**11**

Suppose that we assume particles do impact the walls

- Is the requested DF consistent with data for similar situations?
  - flow path does not plug
  - But flow path does decontaminate gas stream
- Will particles bounce off surfaces they strike?
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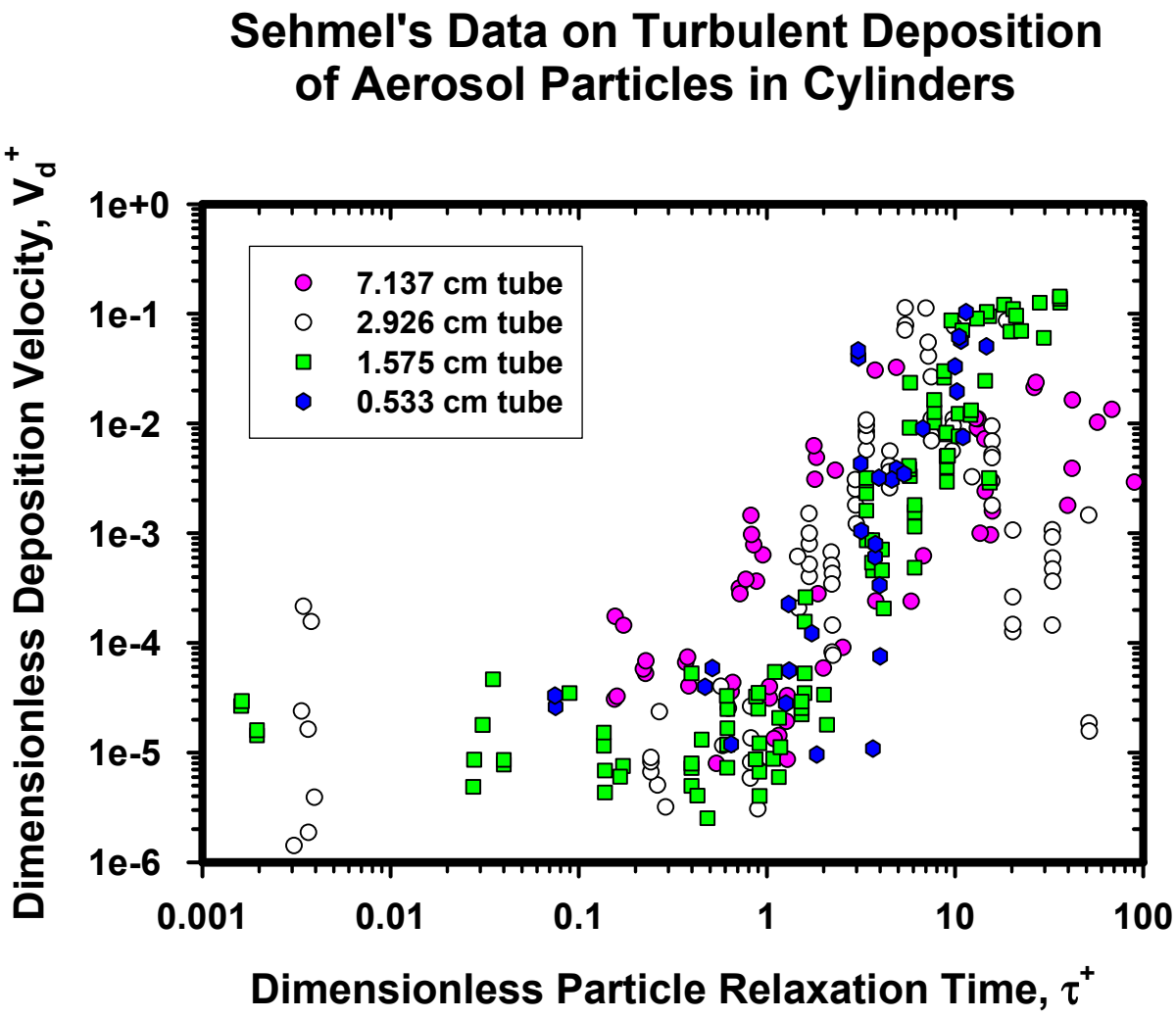
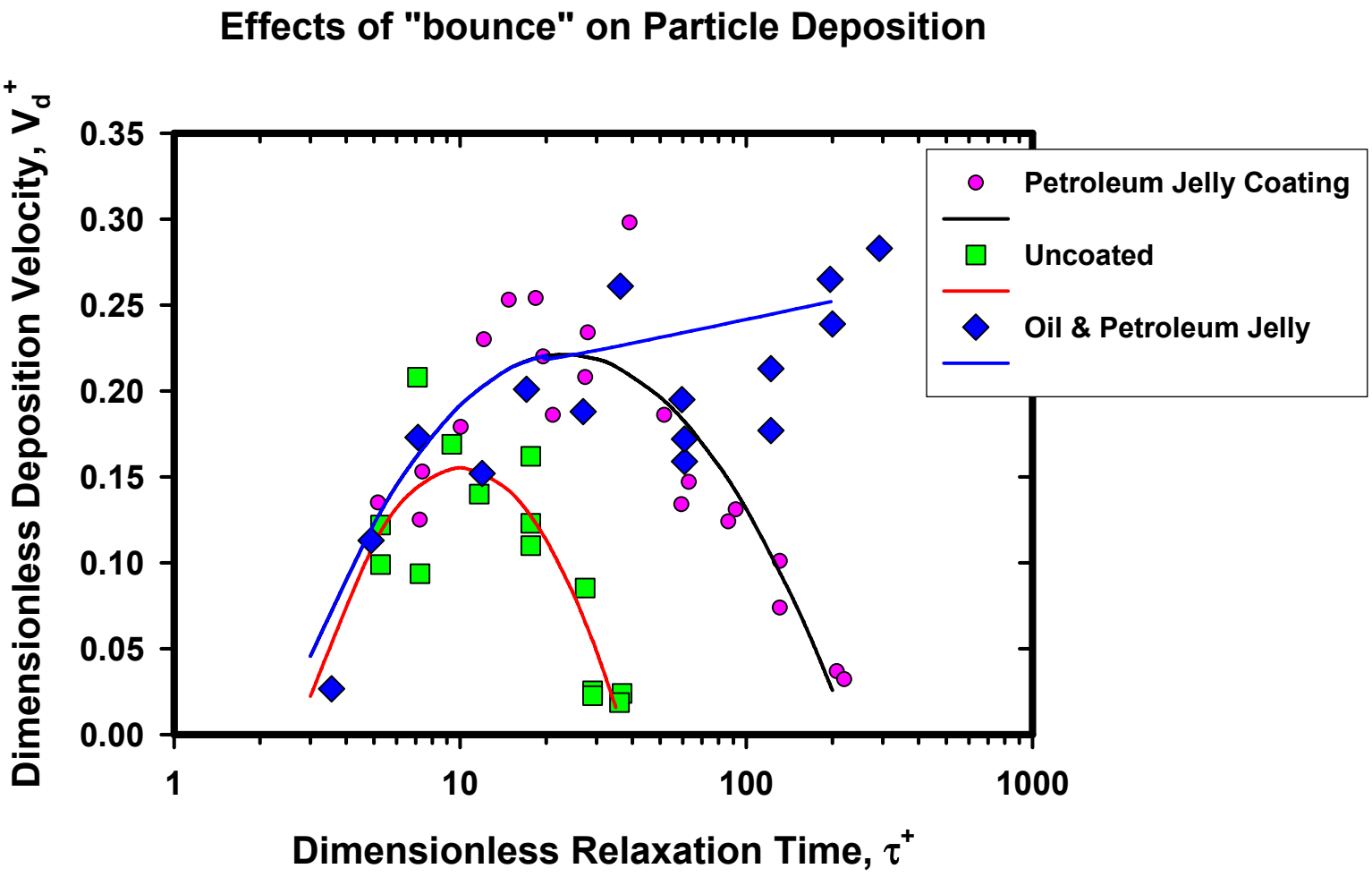
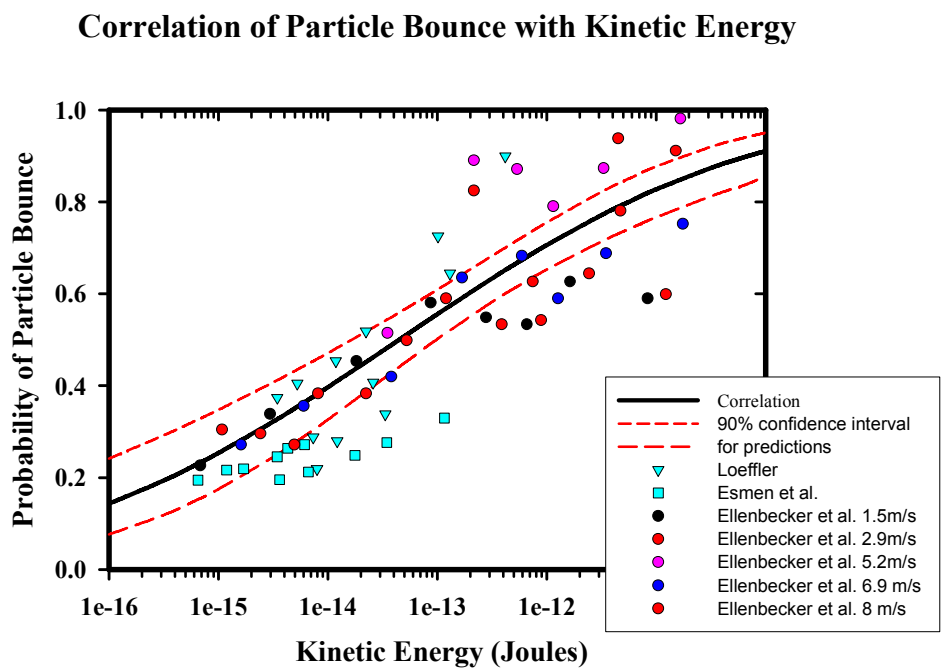

Sehmel's Data on Turbulent Deposition
of Aerosol Particles in Cylinders
7.137 cm tube
2.926 cm tube
1.575 cm tube
0.533 cm tube
Dimensionless Deposition Velocity, V_d^+
1e+0
1e-1
1e-2
1e-3
1e-4
1e-5
1e-6
0.001
0.01
0.1
1
10
100
Dimensionless Particle Relaxation Time, τ^+

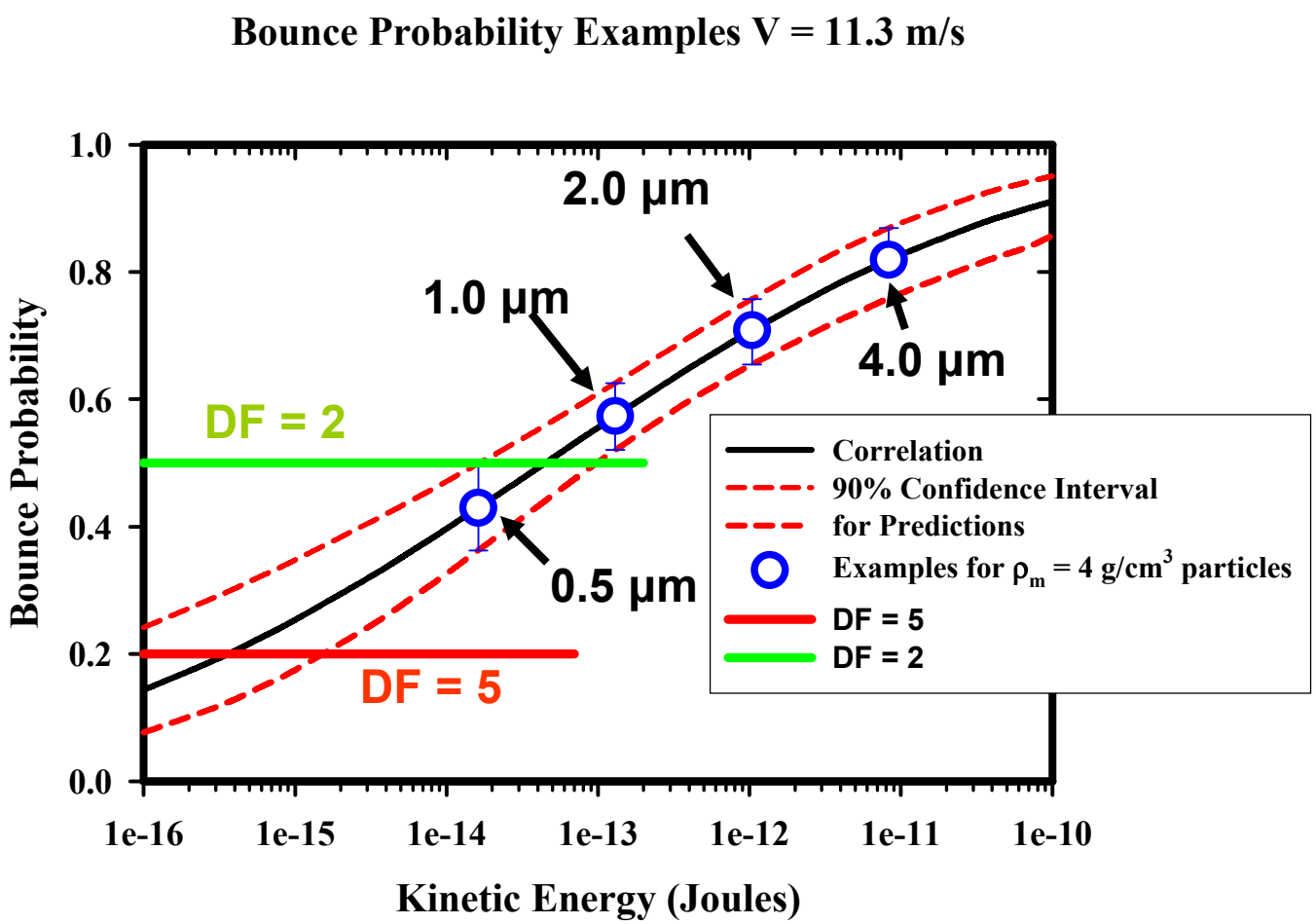

Effects of "bounce" on Particle Deposition
Dimensionless Deposition Velocity, V_d^+
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1
10
100
1000
Dimensionless Relaxation Time, τ^+
Petroleum Jelly Coating
Uncoated
Oil & Petroleum Jelly

Bounce in AP1000 Leak

- Particle residence time in AP1000 leak is ~ 0.14 millisecs.
- To cross leak path and impact wall before exiting the leak path particle velocity must be >11 m/s:
  - KE(1μm) = 1.3×10^{-13} J
  - KE(2μm) = 1.0×10^{-12} J
  - KE(4μm) = 8.3×10^{-12} J



Bounce Will Limit DF Possible If Particles Strike the Walls



Suppose that we assume particles do impact the walls

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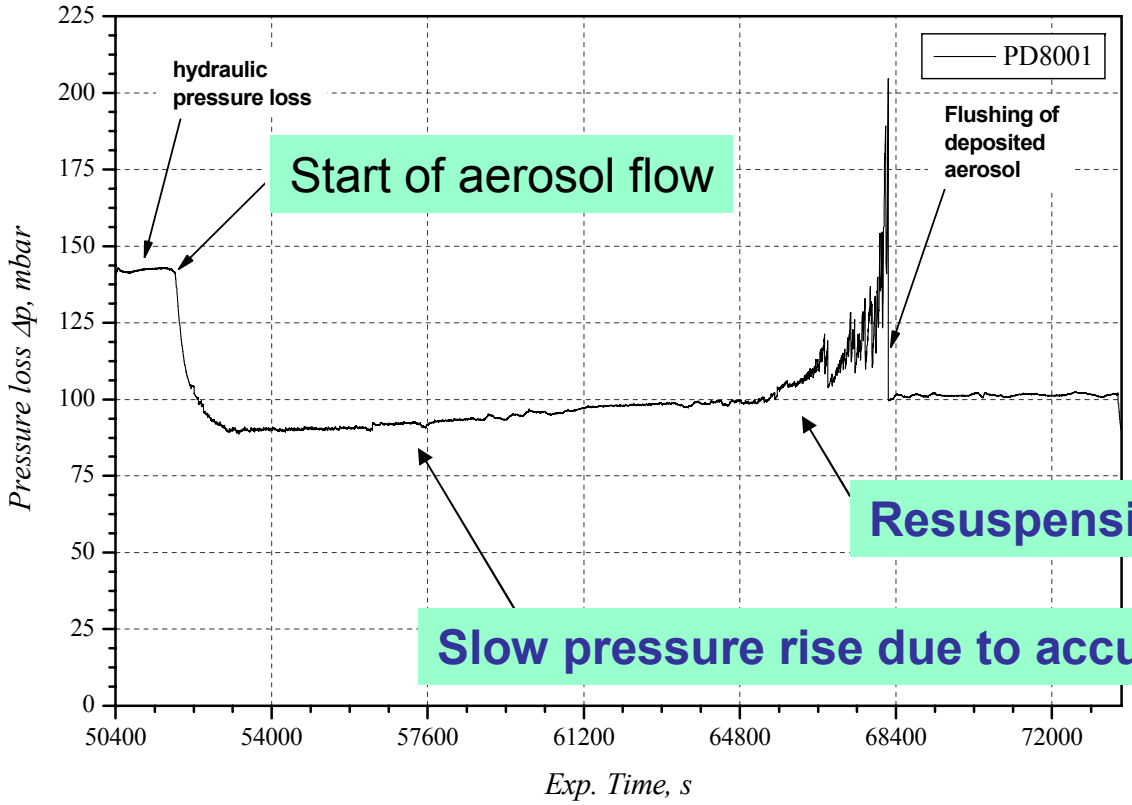
- **Will particles bounce off surfaces they strike?**
- **Will deposited particles resuspend from surfaces into the flow?**

ARTIST Tests

- **Exhibited resuspension and particle breakup in flow through steam generator tubes at velocities of about 96 m/s**

Aerosol Flow Thru a Broken Tube

Inlet aerosol ~3.2 µm AMD Outlet aerosol ~ 0.7 µm DF ~ 1.1



~ 4 mm

High Velocity Gas Streams

- **Known to resuspend deposited particles**
  - **Used to clean surfaces of deposited particles**
- **Resuspension probably augmented by shocks and vibrations to surfaces where particles are deposited in reactor accidents**
  - **Synergism between vibrations and flow in particle resuspension established in experiments by Corn.**
  - **Encouraging ARTIST follow-on to explore this type of resuspension.**

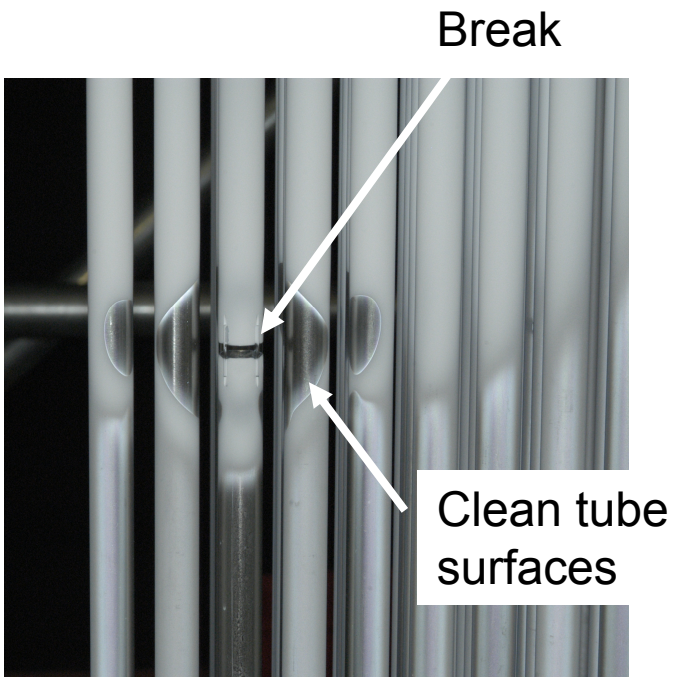


Photo from ARTIST tests shows high velocity gas from tube break prevents particle deposition until flow dissipated.

AP1000 discounts resuspension

- They argue that resuspended particles will be large and redeposit or fall out promptly upon exit from leak
- Not what was observed in ARTIST tests
  - Agglomerate particles (3.2 AMMD) input reduced (~0.7 AMMD) coming out with minimal retention within tube
  - Breakup cause uncertain
    - Impact on tube walls
    - Turbulent forces (research underway in UK)
    - Shock at exit (known to deagglomerate aerosol)

CSE Test

- "Very large fractions of the FP entering the leak point were retained in the condensate flask, averaging 0.94 for iodine and 0.99 for cesium"
- Condensate flask downstream of leak and a needle valve
- Suggests DF by leak and needle valve small:
  - DF(iodine) = 1.064
  - DF(cesium) = 1.01

Decontamination cited by AP1000 dealt with release from the flask after it was heated to dryout.

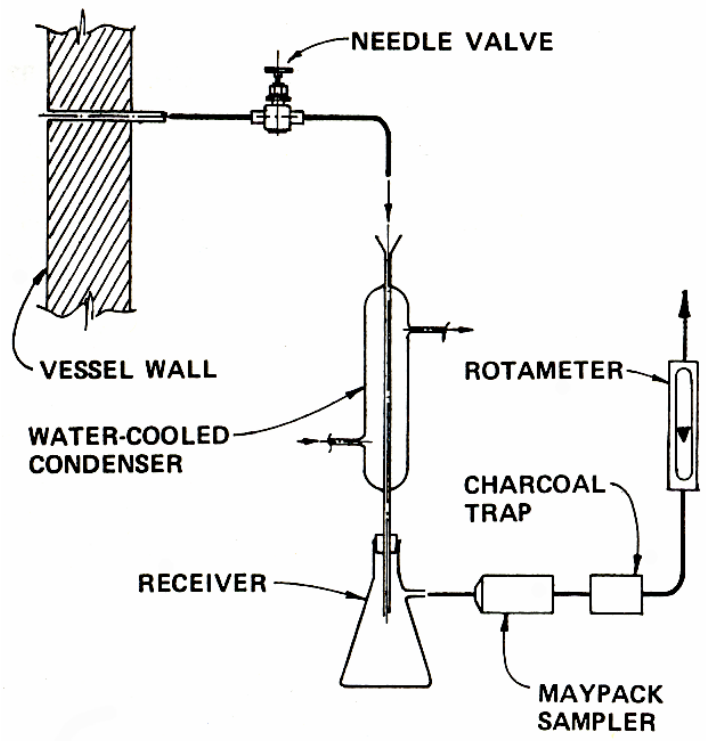


Fig. 9. Sampling train used to collect leaked FPs.

Findings(1)

- **Examination of details of particle behavior in design basis leak has not been done in the past**
- **May necessitate detailed look at the likely leakage that will occur following a design basis accident**
  - **Japan test as well as tests with concrete containments shows this is complicated**
  - **Leakage can grow with time and be much larger than the design basis leak rate**
  - **Analysis may be further complicated by changes in steel containment as a result of accident loads and even diurnal cycling that may reopen plugged leaks or create new leaks**

Findings(2)

- **It is not self-evident that the 1.5 mm diameter leak path chosen for AP1000 is appropriately conservative**
- **Morewitz correlation involves violation of both the Stokes number limit and the relative velocity limit defined by Davies and the less restrictive limits defined by Agrawal and Liu**
  - **Novick shows that when these limits are not violated tubes do not plug**
  - **Substantiated by data for capillaries obtained by Mitchell and coworkers**
  - **AP 1000 conditions are such that deposition by inertial impaction in the leak pathway by inertial mechanisms would not be expected**

Findings(3)

- **Davies criteria and less restrictive criteria from Agrawal and Liu preclude inertial impaction in the leak path opening as hypothesized.**
- **If particles do impact the sides of the leak path, they may bounce or be resuspended by the high velocity flow as observed in tests such as those by Mitchell *et al.* and recent ARTIST tests**
- **Data cited by Morewitz in the development of the correlation used for AP1000 do not support a DF of 5. CSE test results do not support such a high DF.**