



Calculation of Pressure Drop Across a Porous Media Debris Bed on a PWR Sump Screen

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U. S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

ANS 2006 Winter Meeting
November 12-16, 2006

Objectives and Motivation

- Comparisons of test results and analytical approaches indicated the need to develop improved models for particulate/fiber insulation debris beds to conservatively predict
 - pressure drop across and
 - compression of insulation debris on a clogged screen or perforated plate, and
 - provide insight on how variations in debris concentrations can affect pressure drop.

Modeling Approach

- Methods developed for modeling a debris bed using
 - a single homogeneous calculational control volume and
 - two control volumes for heterogeneous debris distribution.

Control Volume Modeling

	↓ Flow Fiber, Particle or “Unsaturated” Particles in Fiber Bed	↓ Flow “Saturated” Particles in Fiber Bed	↓ Flow Fibers “Saturated” Particles in Fiber Bed	↓ Flow Particles “Saturated” Particles in Fiber
Description	Homogeneous “unsaturated” bed	Homogeneous “saturated” bed	Heterogeneous locally “saturated” bed	Heterogeneous locally “over - saturated” bed
Calculational Method	One-volume	One-volume	Two-volume	Two-volume
Head Loss	<ul style="list-style-type: none"> • Best estimate Δp for bed with one debris type • Lower bound Δp for bed with two debris types 	<ul style="list-style-type: none"> • Best estimate Δp for “saturated” bed with two debris types 	<ul style="list-style-type: none"> • Upper bound Δp for “unsaturated” bed with two debris types 	<ul style="list-style-type: none"> • Upper bound Δp for “over-saturated” bed with two debris types

Pressure Drop Calculation

- Calculation based on classical form of porous medium flow (Ergun) equation

$$\frac{\Delta p_{\text{debris}}}{L} = \underbrace{\mu V S_v^2 \frac{X^3}{K(X) (1+X)^2} \frac{(1-\epsilon)^2}{\epsilon^3}}_{\text{Viscous Term}} + b \underbrace{\left[\frac{(1-\epsilon) \mu S_v}{\rho V 6} \right]^c \frac{\rho V^2 S_v}{6} \frac{(1-\epsilon)}{\epsilon^3}}_{\text{Kinetic Term}}$$

- The Viscous Term uses
 - the Kozeny-Carman equation to relate permeability (K), porosity (ϵ) and the debris specific surface area (S_v), and
 - a dimensionless permeability function to relate the void ratio to permeability by using the Happel free surface model for
 - a bed with flow perpendicular to fiber cylinders
 - a bed composed of spherical particles.
- The Kinetic Term uses
 - a semi-empirical term based on relations for
 - a woven metal screen of any weave and
 - for beds composed of spherical particles.
 - Calculations indicate that the kinetic term contributes < 8% of the total pressure drop; therefore, the exact values of b and c is not critical to the pressure drop calculation.

Porous Medium Compression

- Analytical model uses a method to predict debris bed compressibility for irreversible and elastic behavior.
 - First compression during increase to maximum velocity is assumed to be a nonrecoverable, irreversible process.

$$X / X' = (P_m / P_m')^{-N}$$

where X' void ratio at P_m' at compression start
 P_m' mechanical stress at compression

- After the first compression the bed is assumed to be elastic with constant compressibility.

$$X / X(P_{\max}) = \exp \left[N - \frac{N P_m}{P_{\max}} \right]$$

where P_{\max} highest compressive stress
 $X(P_{\max})$ void ratio at P_{\max}

- From PNNL test data, $N \approx 0.236$.

Information Needed for Calculations

- Debris material properties determined from PNNL test data

Debris	Material Density (lbm/ft ³)	Specific Surface Area (ft ⁻¹)
Nukon Fibers	175	300,000
CalSil Particles	115	650,000
Fiberglass Fibers in CalSil	175	300,000

- Initial bed thickness at calculation start

- A relation for bed thickness versus debris mass is obtained from PNNL test data at a bed formation velocity of 0.1 ft/s.

$$L_{\text{initial}} = \frac{(X_{\text{Nukon}} + 1)}{A} \frac{m_{\text{Nukon}}}{Q_{\text{Nukon}}} + \frac{(X_{\text{CalSil}} + 1)}{A} \frac{m_{\text{CalSil}}}{Q_{\text{CalSil}}}$$

- From PNNL test data, the values for the void ratio at bed formation are determined to be $X_{\text{Nukon}} = 30$, and $X_{\text{CalSil}} = 6.2$

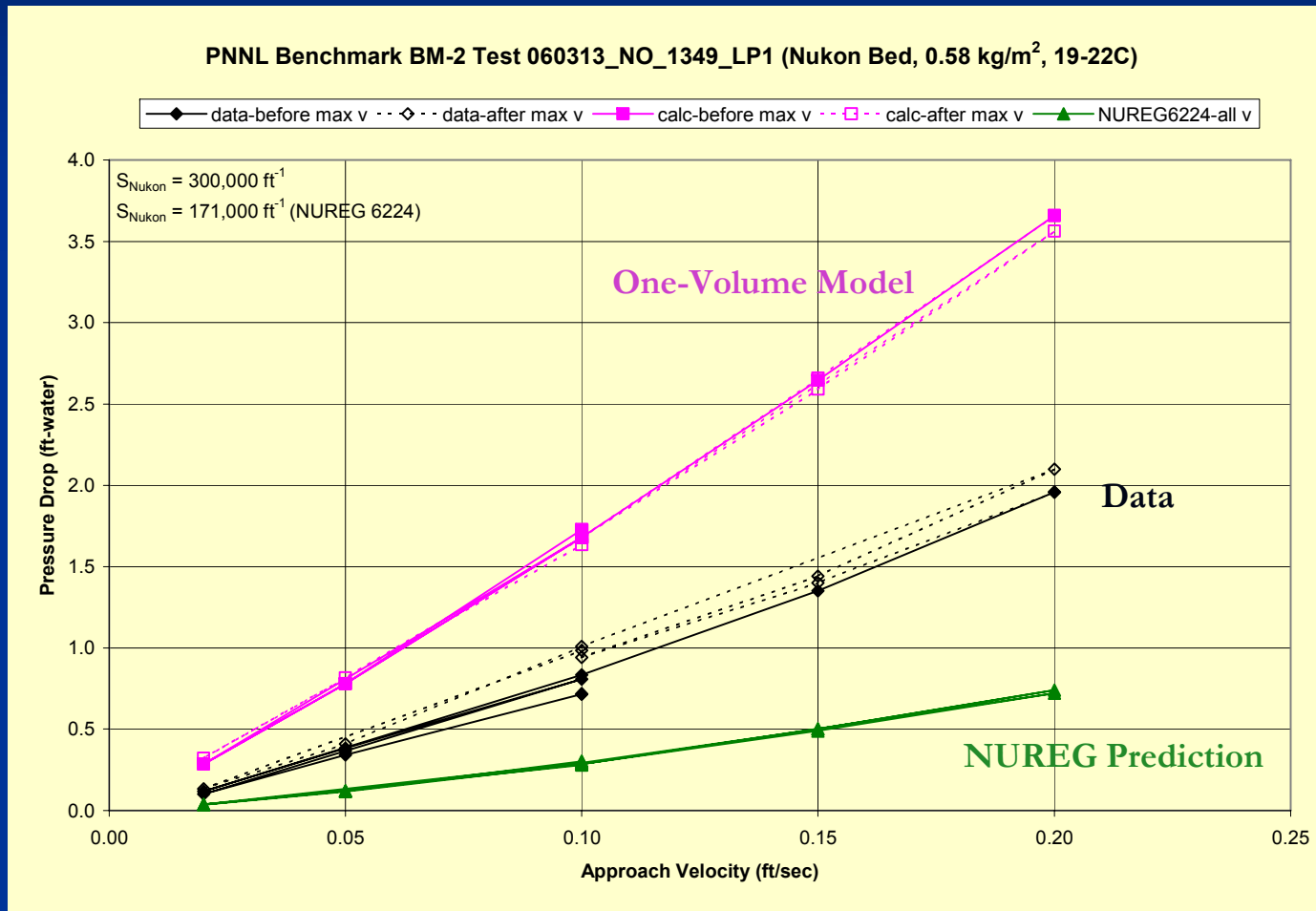
Information Needed for Calculations

- Mass of constituents in debris bed
 - PNNL debris bed mass measurements indicate that only a fraction of the mass added to the test loop is deposited in the debris bed.
 - For Nukon-only tests
 - 79% to 100% of added Nukon mass deposited
 - For Nukon/CalSil tests
 - 70% to 100% of added Nukon mass deposited
 - 10% to 90% of added CalSil mass deposited
 - For CalSil-only tests
 - 5% to 17% of added CalSil mass deposited
- Relation for maximum particulate concentration (“saturation”) condition in a fiber bed.
 - This effect is possible in beds of all thicknesses, but had initially been observed in thin beds and called a “thin bed” effect.

Comparisons with Test Data

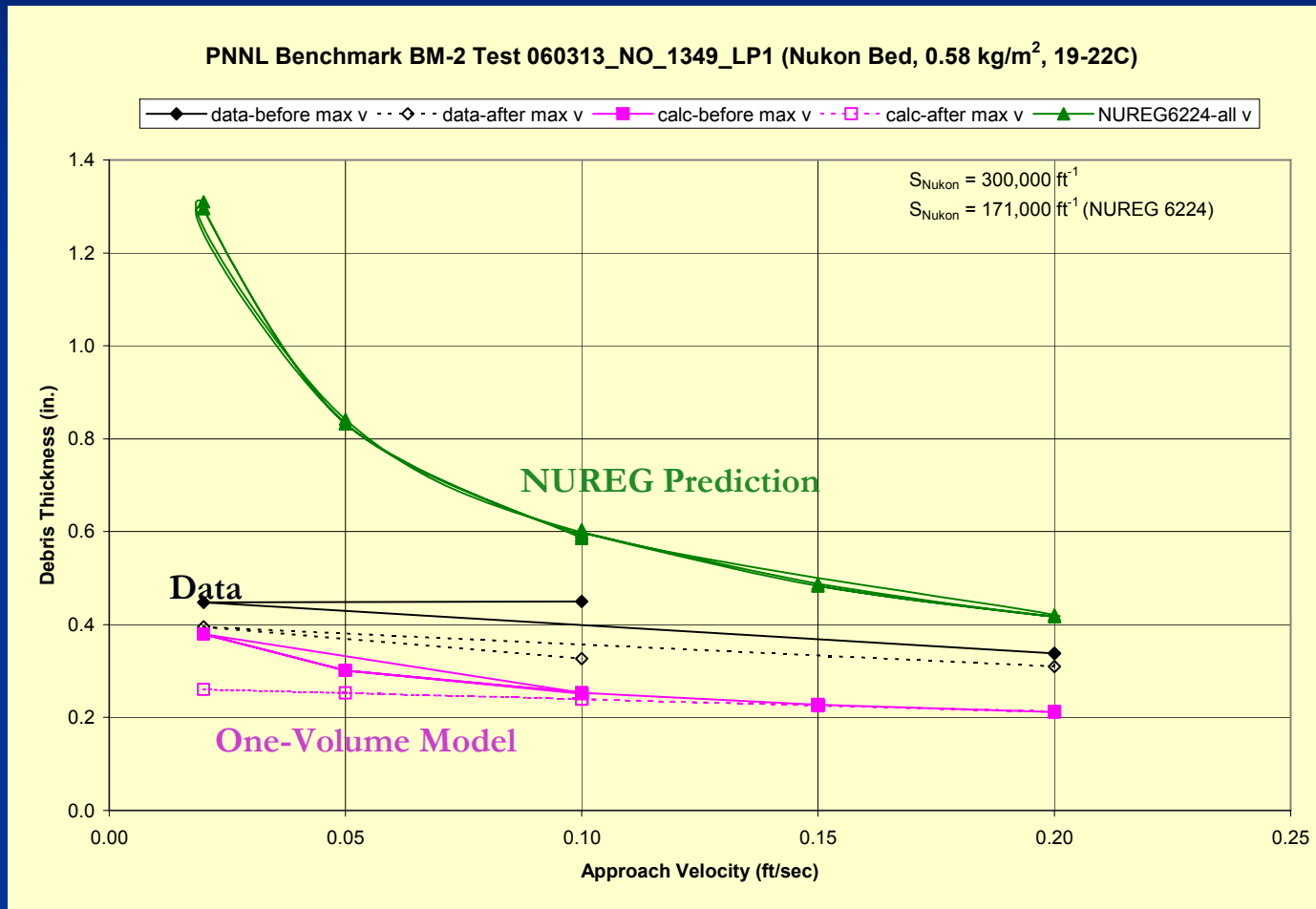
- One-volume Calculations compared to results from
 - PNNL tests
 - ANL tests
 - LANL/UNM tests
- Two-volume Calculations compared to results from
 - PNNL tests
 - LANL/UNM tests

Pressure Drop for Nukon-Only Test



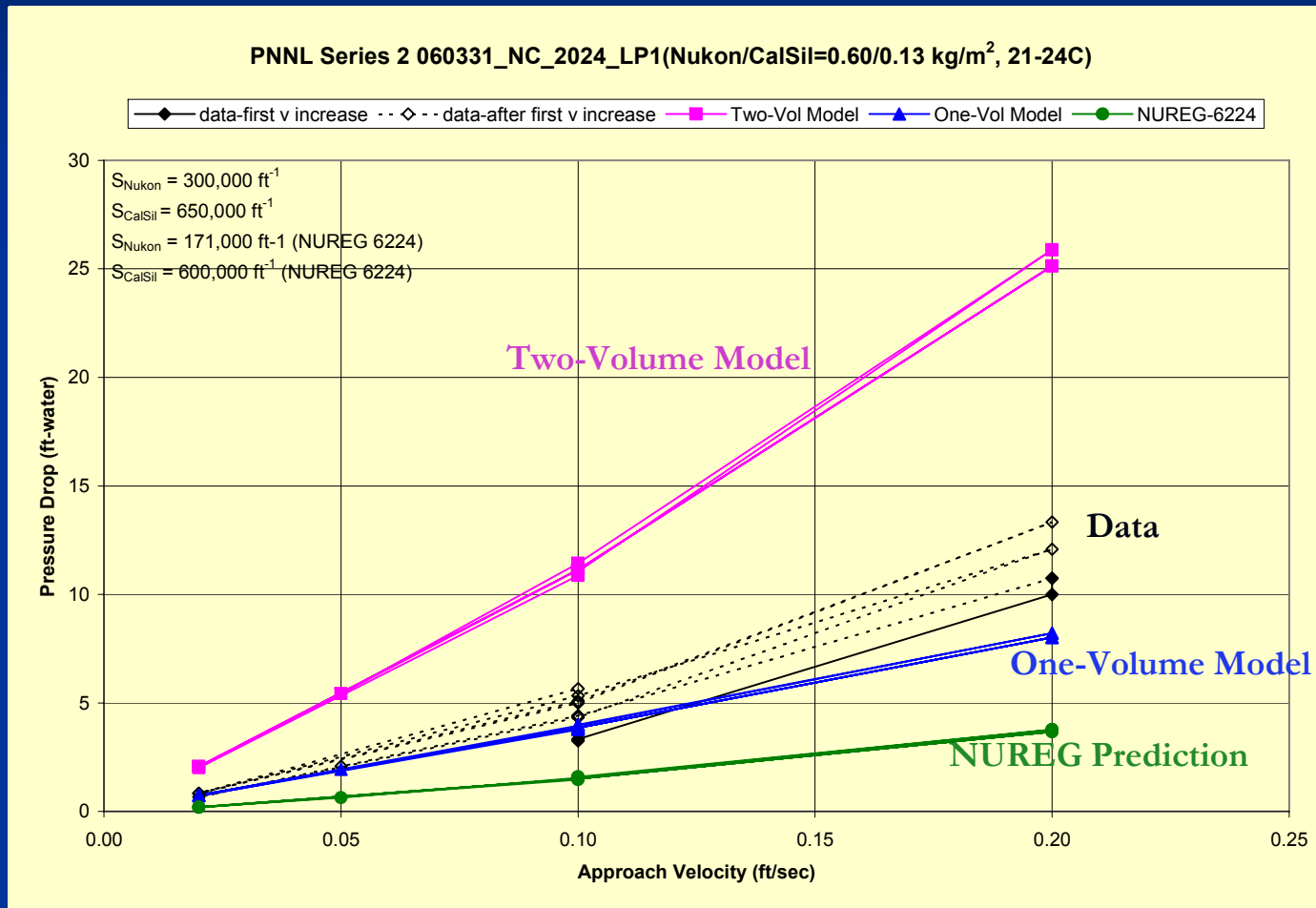
- One-volume predictions are comparative or higher than test data.

Bed Thickness for Nukon-Only Test



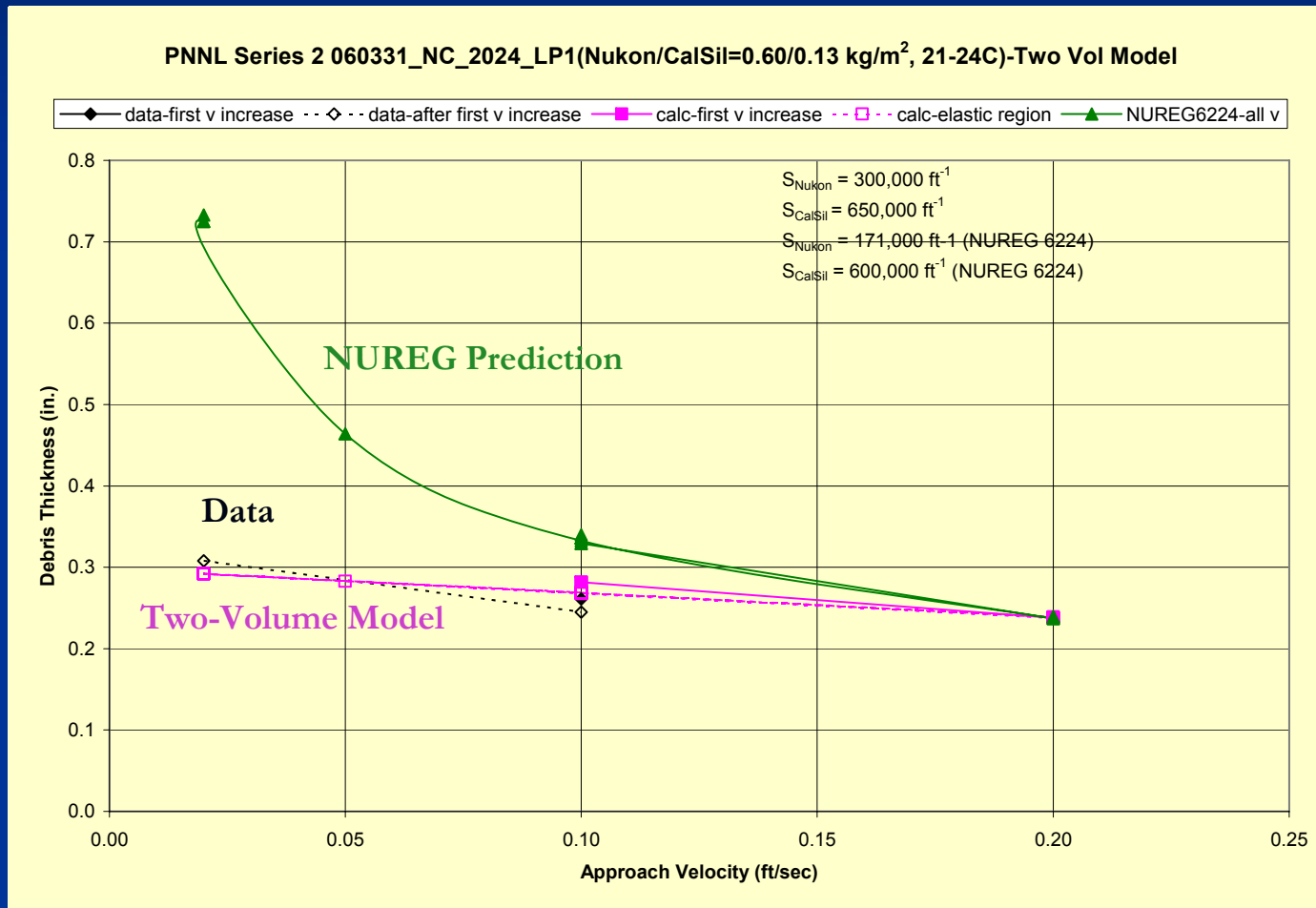
- One-volume predictions are close to test data.

Pressure Drop for Nukon/CalSil Test



- Two-volume predictions provide an upper bound.
- One-volume predictions provide a lower bound for test data.

Bed Thickness for Nukon-CalSil Test



- Two-volume predictions are close to test data.

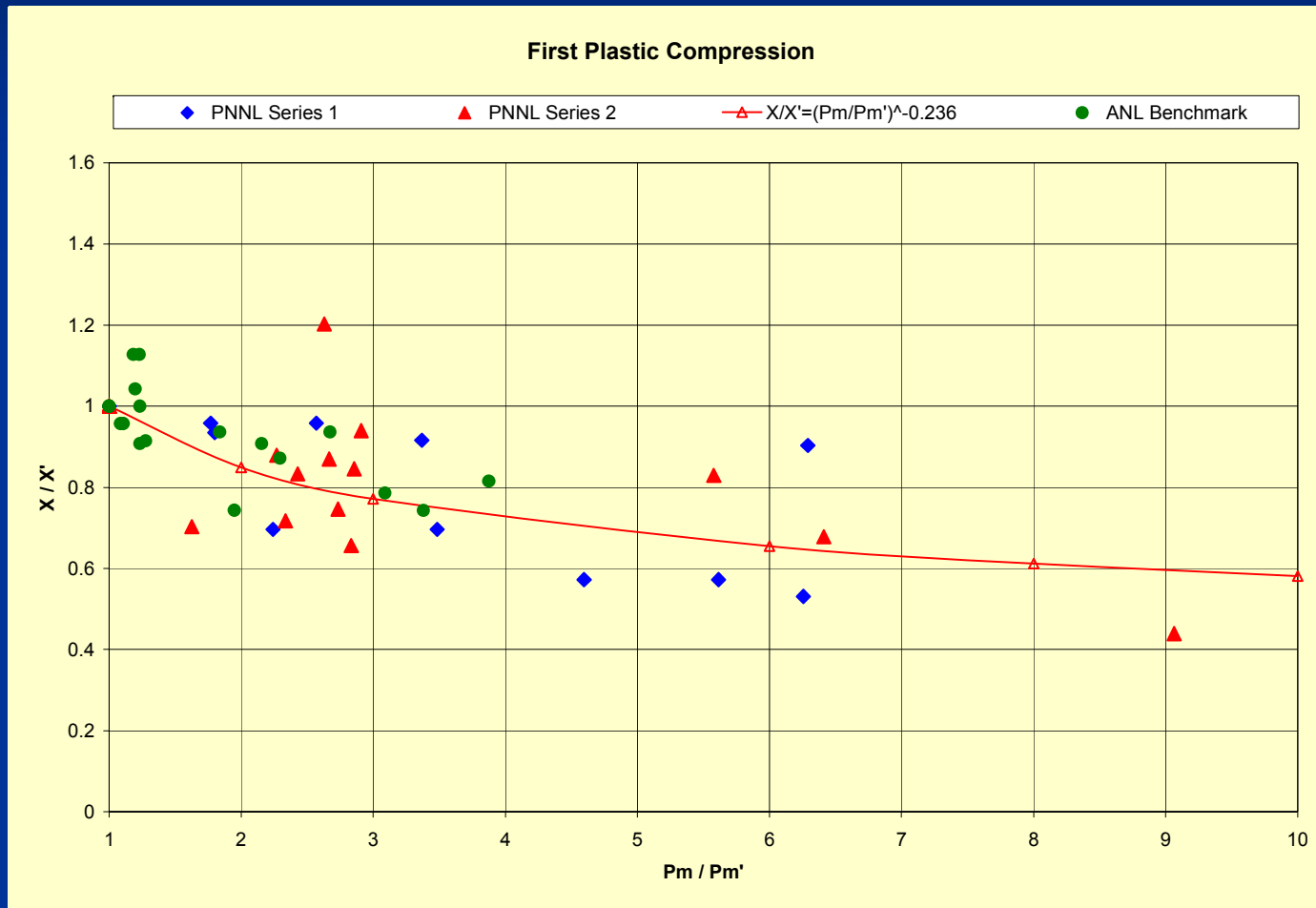
Conclusions

- One-volume Calculations
 - Predictions for Nukon-only tests provide comparative or higher pressure drops for all PNNL, ANL and LANL/UNM test data.
 - Predictions for Nukon/CalSil tests provide lower pressure drop when compared to PNNL test data.
- Two-volume Calculations
 - Predictions for Nukon/CalSil tests provide comparative or higher pressure drops for PNNL and LANL/UNM test data .
- Two-volume calculational method can be improved.
- Bed thickness predictions for all cases are comparative to measurements.

Head Loss Modeling

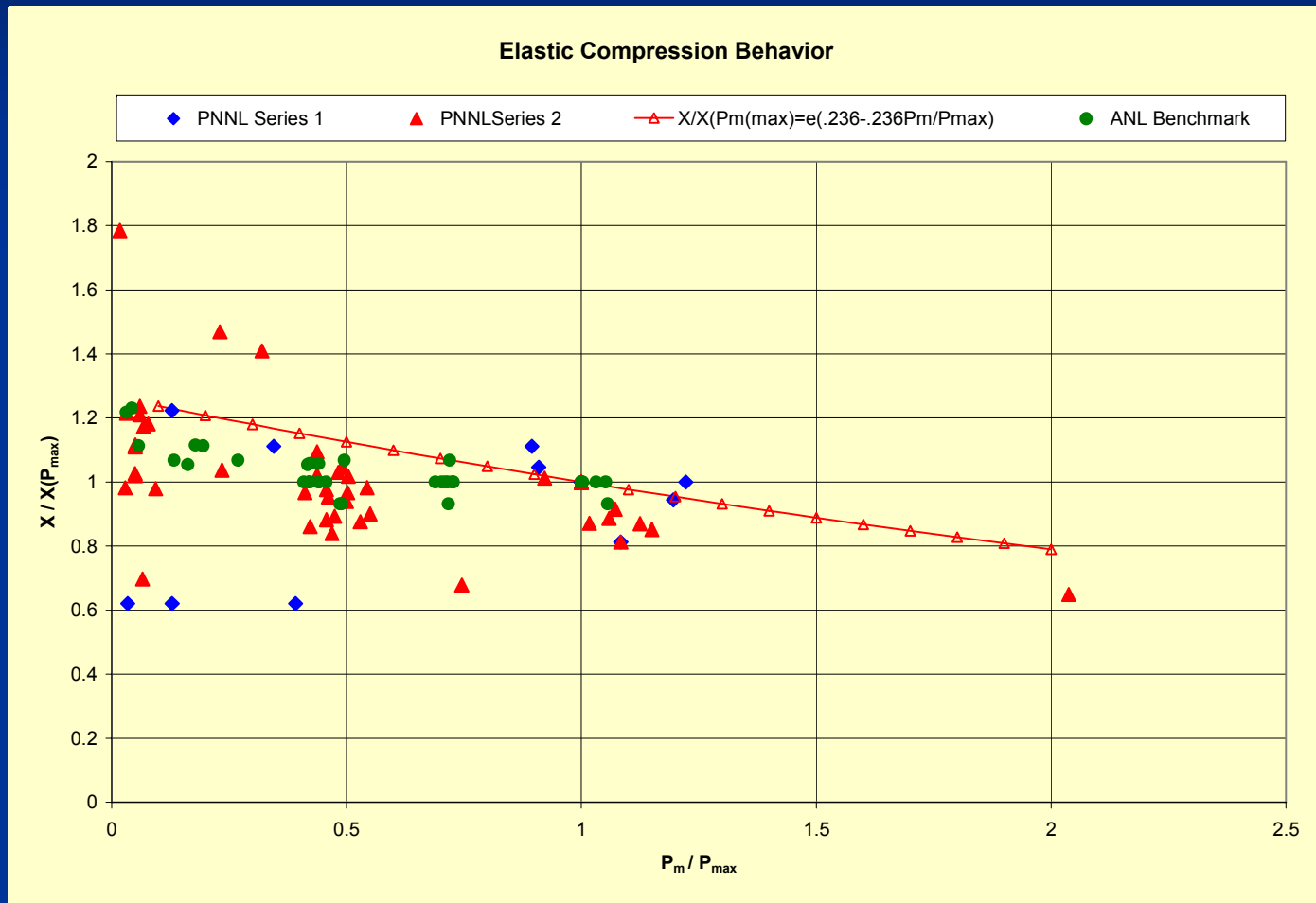
- Backup Slides

Head Loss Modeling



- Using the PNNL test data for bed compression during the first velocity increase, the debris bed void ratio is best fit to the mechanical stress ratio using an exponent of 0.236.

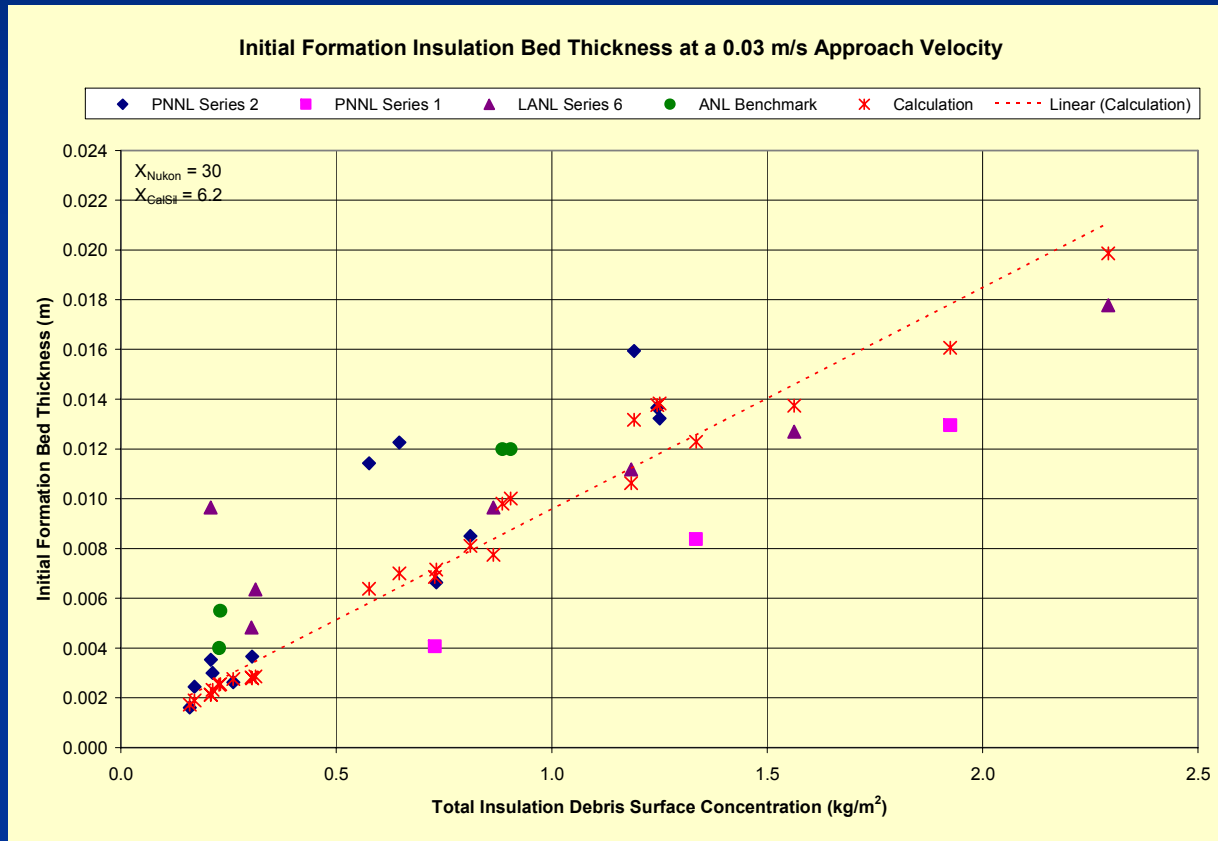
Head Loss Modeling



- Using the PNNL test data for the later elastic bed compressions, the debris bed void ratio is best fit to the mechanical stress ratio using an exponent of 0.236.

Information Needed from Testing

- Initial bed thickness at calculation start



- A relation for bed thickness versus debris mass at bed formation is obtained from the PNNL test data at bed formation velocity of 0.1 ft/s.

$$L_{\text{initial}} = \frac{(X_{\text{Nukon}} + 1)}{A} \frac{m_{\text{Nukon}}}{Q_{\text{Nukon}}} + \frac{(X_{\text{CalSil}} + 1)}{A} \frac{m_{\text{CalSil}}}{Q_{\text{CalSil}}}$$

Information Needed from Testing

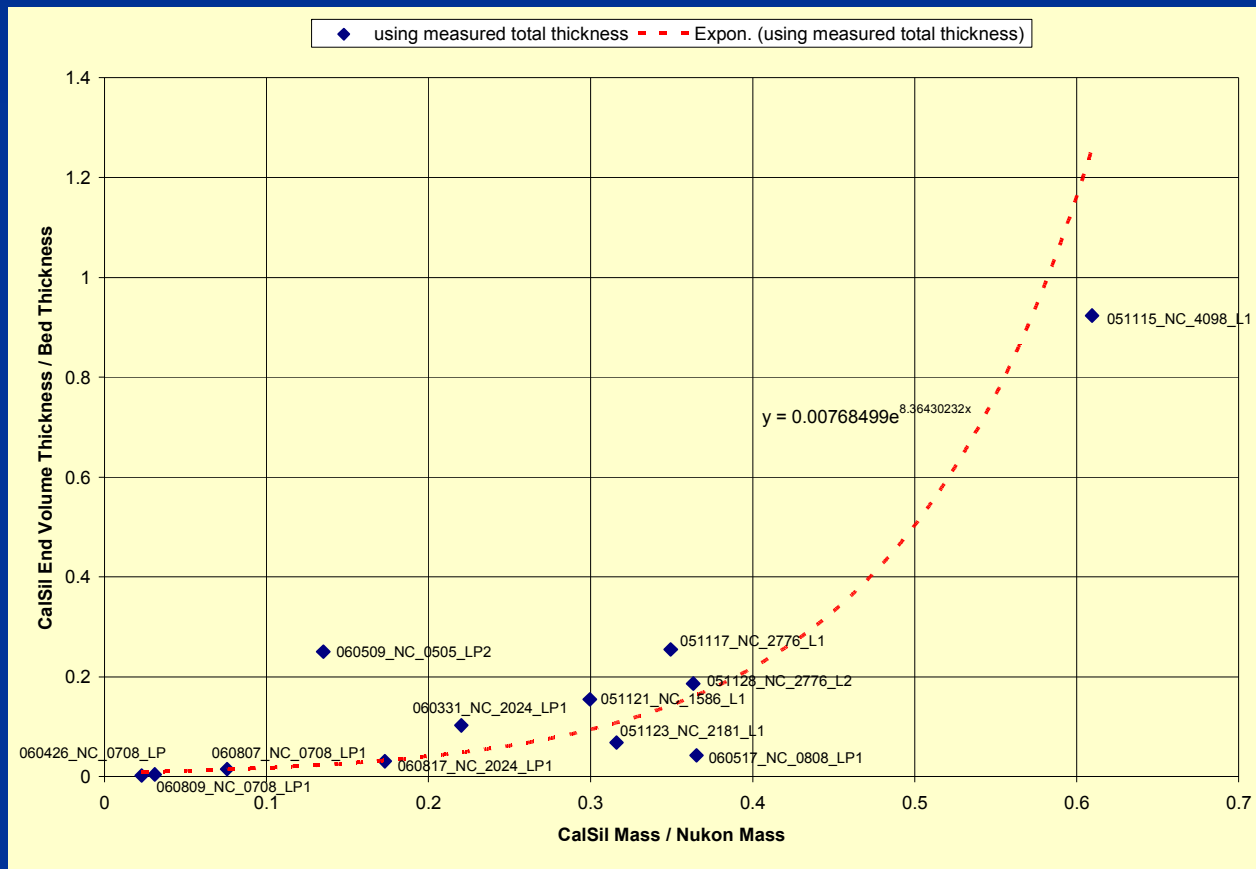
- Actual material masses in debris bed

Test	Debris Bed Mass / Added Mass		
	Nukon	CalSil	Total
Series 1 Tests (Using Metal Screen)			
051108_NO_3067_L1	1.086	NA	1.086
060125_NO_3067_L1	1.045	NA	1.045
051110_NC_0595_L1	0.801	0.434	0.679
051115_NC_4098_L1	0.843	0.934	0.875
051117_NC_2776_L1	0.996	0.696	0.896
051121_NC_1586_L1	0.988	0.592	0.856
051123_NC_2181_L1	1.008	0.637	0.884
051128_NC_2776_L2	0.931	0.677	0.846
Series 2 Tests (Using Perforated Plate)			
060321_NO_0405_LP1 (BM-1)	0.785	NA	0.785
060313_NO_1349_LP1 (BM-2)	0.796	NA	0.796
060425_NO_2703_LP1, LP2, LP3	0.858	NA	0.858
060731_NO_2703_LP1, LP2	0.862	NA	0.862
060802_NO_2703_LP1, LP2	0.821	NA	0.821
060512_CO_8108_LP1, LP2, LP3	Bed	Incomplete	0.100
060323_NC_1619_LP1 (BM-3)	0.865	0.140	0.744
060331_NC_2024_LP1	0.829	0.365	0.6739
060817_NC_2024_LP1, LP2	0.955	0.330	0.747
060404_NC_2698_LP1	0.723	0.468	0.5956
060509_NC_0505_LP1	0.848	0.458	0.770
060426_NC_0708_LP1, LP2	0.961	0.029	0.561
060807_NC_0708_LP1, LP2	1.118	0.113	0.686
060809_NC_0708_LP1, LP2	0.715	0.030	0.421
060517_NC_0808_LP1, LP2	1.003	0.368	0.686

The PNNL debris bed mass measurements indicate that only a fraction of the total debris mass added to the test loop is deposited in the debris bed.

Information Needed from Testing

- Relation for maximum particulate concentration (“saturation”) condition in a fiber bed.
 - This effect is possible in beds of all thicknesses, but had initially been observed in thin beds and called a “thin bed” effect.



Head Loss Testing and Modeling

Testing Summary

- Testing with screen and perforated plate provide similar results.
- Head loss measurements decrease with increased temperature, but results affected by test performance and conditions.
- Debris preparation and loading sequence for particle/fiber can affect head loss.
- Complete CalSil-only particle bed could not be formed.

Head Loss Modeling

- From literature, the pressure drop across a porous medium has been calculated using:

- Darcy Equation for viscous flow

$$\frac{\Delta p}{L} = \frac{\mu V}{K}$$

- Ergun Equation for packed bed at higher Reynolds numbers

$$\frac{\Delta p}{L} = \frac{\text{Viscous Term}}{D_p^2} + \frac{\text{Kinetic Term}}{D_p}$$
$$\frac{\Delta p}{L} = \frac{150 \mu V}{D_p^2} \frac{(1-\epsilon)^2}{\epsilon^3} + \frac{1.75 \rho V^2}{D_p} \frac{(1-\epsilon)}{\epsilon^3}$$

Head Loss Modeling

- The Ergun equation can be written using the material specific surface area, S_v .
 - For a spherical particle bed, $S_v = 6 / D_p$

$$\frac{\Delta p}{L} = 4.167 \mu V S_v^2 \frac{(1-\epsilon)^2}{\epsilon^3} + 0.2917 \rho V^2 S_v \frac{(1-\epsilon)}{\epsilon^3}$$

- For cylindrical fibers, $S_v = 4 / D_p$

$$\frac{\Delta p}{L} = 9.375 \mu V S_v^2 \frac{(1-\epsilon)^2}{\epsilon^3} + 0.4375 \rho V^2 S_v \frac{(1-\epsilon)}{\epsilon^3}$$

Viscous Term for Pressure Drop

- Using the Kozeny-Carman equation,

$$K = \frac{\varepsilon^3}{k_k S_v^2 (1-\varepsilon)^2} \quad \text{where } k_k \text{ is the Kozeny constant}$$

- The general form of the Ergun equation can be written as:

$$\frac{\Delta p}{L} = k_k \mu V S_v^2 \frac{(1-\varepsilon)^2}{\varepsilon^3} + \beta \rho V^2 S_v \frac{(1-\varepsilon)}{\varepsilon^3}$$

Viscous Term for Pressure Drop

- If a dimensionless permeability function is defined as:

$$K(X) = \frac{X^3}{k_k (1+X)^2} \quad \text{where the void ratio } X = \text{Vol}_{\text{void}}/\text{Vol}_{\text{solid}}$$

- Then, k_k can be written as:

$$k_k = \frac{X^3}{K(X) (1+X)^2}$$

Viscous Term for Pressure Drop

- Using the Happel free surface model,
 - For a bed with flow perpendicular to fiber cylinders

$$K(X) = -0.5 + 0.5 \ln(1+X) + \frac{1}{(2 + 2X + X^2)}$$

for $1.0 \times 10^{-4} < X < 0.995$

- For a bed composed of spherical particles

$$K(X) = 2 - \frac{3}{(1+X)^{1/3}} + \frac{5}{3(1+X)^{5/3} + 2}$$

for $1.0 \times 10^{-4} < X < 0.995$

Porous Medium Pressure Drop

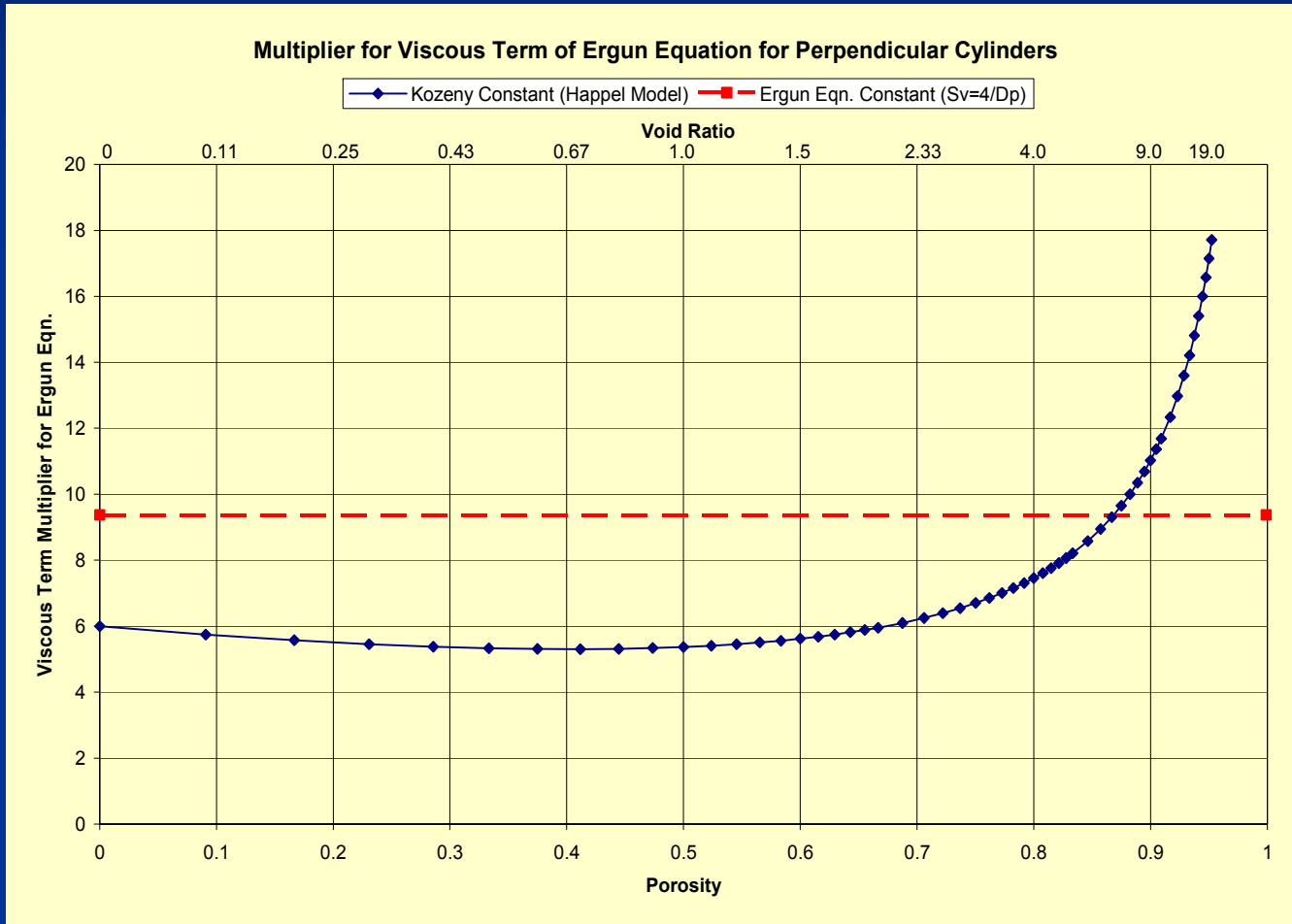
- General Form of Ergun Equation

$$\frac{\Delta p}{L} = \underbrace{\alpha \mu V S_v^2 \frac{(1-\epsilon)^2}{\epsilon^3}}_{\text{Viscous Term}} + \underbrace{\beta \rho V^2 S_v \frac{(1-\epsilon)}{\epsilon^3}}_{\text{Kinetic Term}}$$

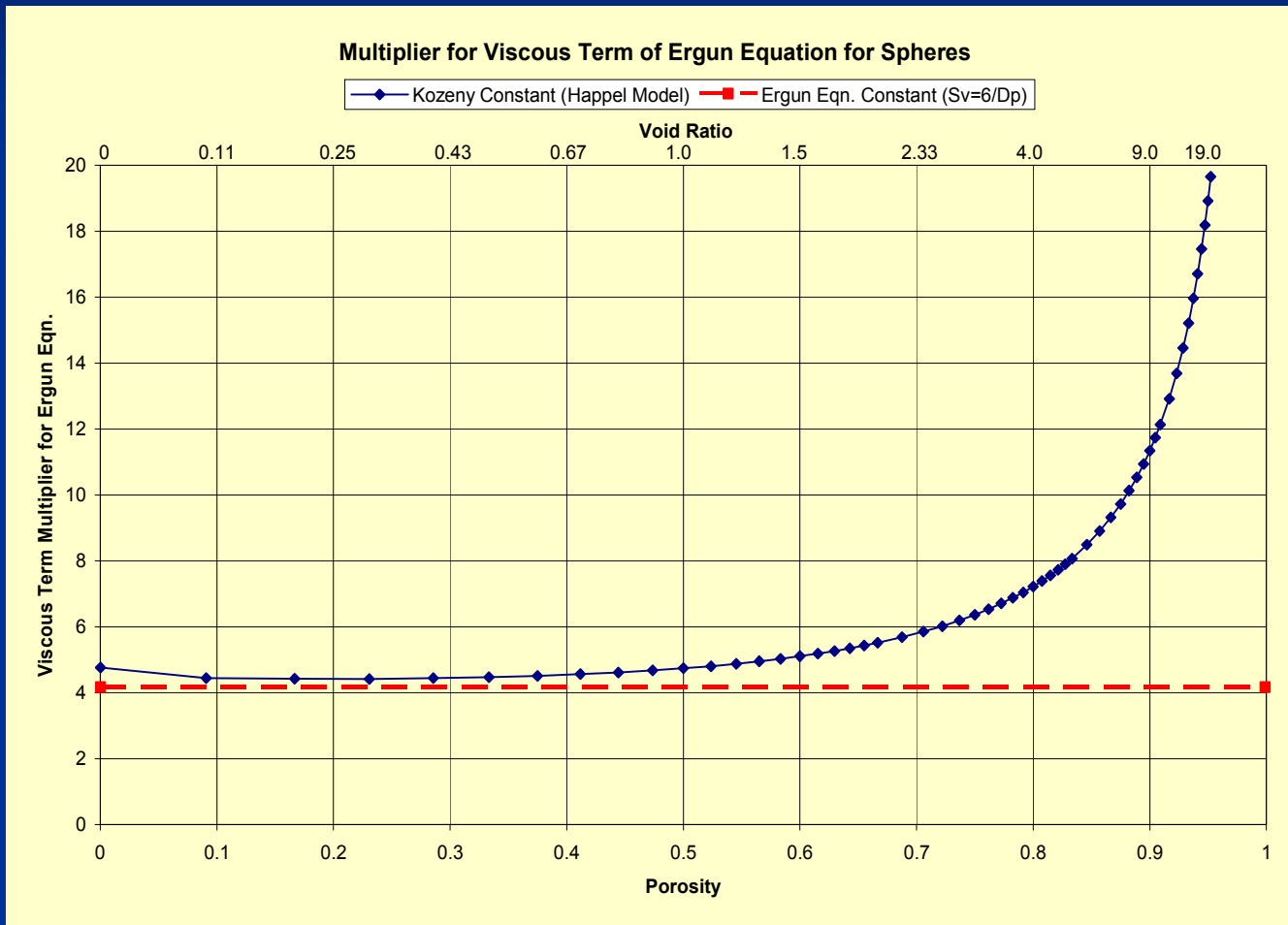
- Head loss equation with viscous term from Darcy equation

$$\frac{\Delta p}{L} = \underbrace{\frac{\mu V}{K}}_{\text{Darcy}} + \frac{\beta \rho V^2 S_v (1-\epsilon)}{\epsilon^3}$$

Viscous Term for Pressure Drop



Viscous Term for Pressure Drop



Kinetic Term for Pressure Drop

- Semi-empirical pressure drop relation

$$\frac{\Delta p}{L} = \underbrace{\frac{a \mu V S_v^2}{36} \frac{(1-\epsilon)^2}{\epsilon^3}}_{\text{Viscous Term}} + \underbrace{b \left[\frac{(1-\epsilon) \mu S_v}{\rho V 6} \right]^c \frac{\rho V^2 S_v}{6} \frac{(1-\epsilon)}{\epsilon^3}}_{\text{Kinetic Term}}$$

For plain square type woven metal screens

$$a = 250, b = 1.69, c = 0.071$$

$$\text{for } 0.5 < \frac{Re}{(1-\epsilon)} < 9.85 \times 10^4 \text{ and } 0.602 < \epsilon < 0.919$$

For a bed composed of spherical particles

$$a = 150, b = 3.89, c = 0.13$$

$$\text{for } 440 < Re < 7.92 \times 10^4 \text{ and } 0.38 < \epsilon < 0.44$$

Porous Medium Pressure Drop

$$\frac{\Delta p_{\text{debris}}}{L} = \mu V S_v^2 \frac{K(X)}{(1+X)^2} \frac{(1-\epsilon)^2}{\epsilon^3} + b \left[\frac{(1-\epsilon) \mu S_v}{\rho V} \right]^c \frac{\rho V^2 S_v}{6} \frac{(1-\epsilon)}{\epsilon^3}$$

Definitions

$K(X)$ dimensionless permeability function
dependent on debris type

Δp_{debris} pressure drop across debris bed

L debris bed thickness

V approach velocity

X void ratio ($\text{Vol}_{\text{void}} / \text{Vol}_{\text{solid}}$)

ϵ porosity ($\text{Vol}_{\text{void}} / \text{Vol}_{\text{total}}$)

Values determined from tests

S_v debris specific surface area

b, c empirical values dependent on
debris type

- Calculations indicate that the kinetic term contributes < 8% of the total pressure drop; therefore, the exact values of b and c is not critical to the pressure drop calculation.

Head Loss Modeling

Equation for Nukon and CalSil Mixture Debris Beds

$$\Delta p_{\text{total}} = \Delta p_{\text{debris bed}} + \Delta p_{\text{irreversible loss}}$$

$$\frac{\Delta p_{\text{debris}}}{L_{\text{debris}}} = \left[\frac{S_{\text{Nukon}}^2 X_{\text{Nukon}}^3 (1-\epsilon_{\text{Nukon}})^2}{K(X_{\text{Nukon}}) (1+X_{\text{Nukon}})^2 \epsilon_{\text{Nukon}}^3} + \frac{S_{\text{CalSil}}^2 X_{\text{CalSil}}^3 (1-\epsilon_{\text{CalSil}})^2}{K(X_{\text{CalSil}}) (1+X_{\text{CalSil}})^2 \epsilon_{\text{CalSil}}^3} \right] \mu V +$$

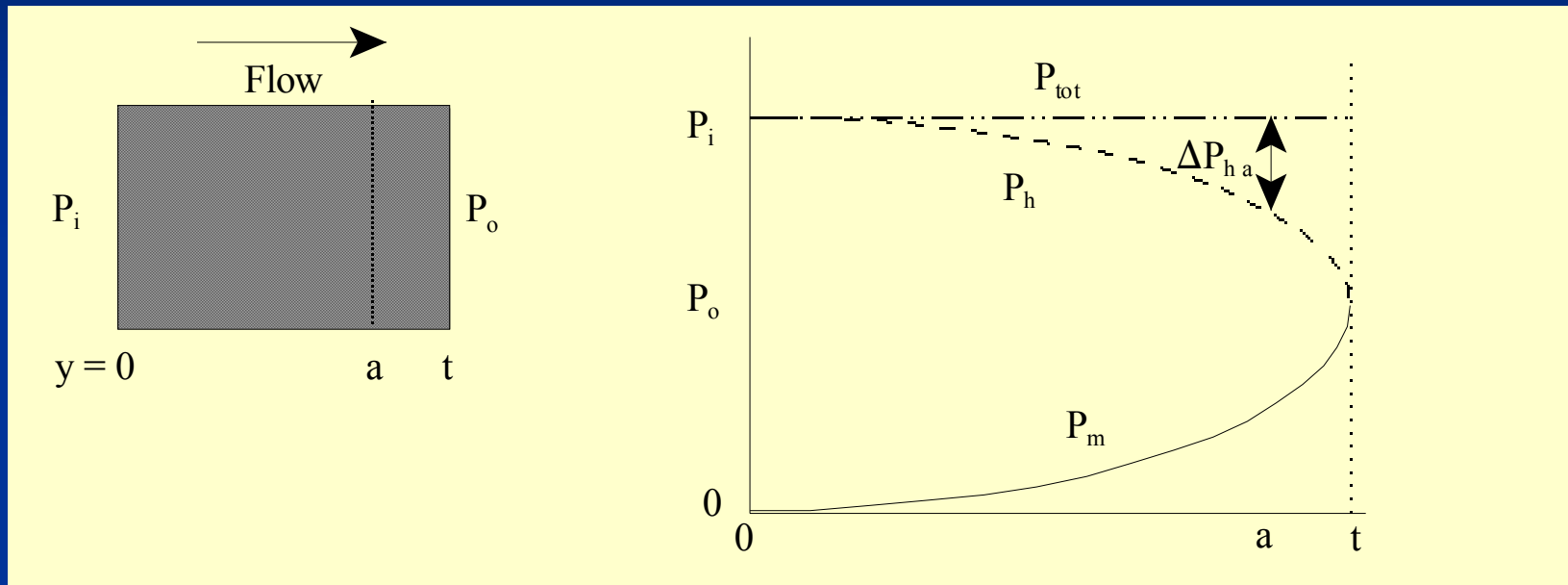
$$\left[S_{\text{Nukon}} 1.95 \left[\frac{(1-\epsilon_{\text{Nukon}}) \mu S_{\text{Nukon}}}{\rho V 6} \right]^{0.071} \frac{(1-\epsilon_{\text{Nukon}})}{\epsilon_{\text{Nukon}}^3} + S_{\text{CalSil}} 3.89 \left[\frac{(1-\epsilon_{\text{CalSil}}) \mu S_{\text{CalSil}}}{\rho V 6} \right]^{0.13} \frac{(1-\epsilon_{\text{CalSil}})}{\epsilon_{\text{CalSil}}^3} \right] \frac{\rho V^2}{6}$$

for Nukon with $0.5 < \frac{Re}{(1-\epsilon)} < 9.85 \times 10^4$ and $0.564 < \epsilon < 0.919$

for CalSil with $440 < Re < 7.92 \times 10^4$ and $0.38 < \epsilon < 0.44$

$$\Delta p_{\text{irreversible loss}} = \Delta p_{\text{debris entrance}} + \Delta p_{\text{debris exit}}$$

Head Loss Modeling



$$P_{\text{tot}} = P_m + P_h$$

At entrance, $y = 0$,

$$P_h = P_i,$$

$$\Delta P_h = 0,$$

$$P_m = 0$$

At exit, $y = t$,

$$P_h = P_o,$$

$$\Delta P_h = P_i - P_o,$$

$$P_m = P_i - P_o$$

At $y = a$,

$$P_h = P_i - \Delta P_{ha}$$

$$P_m = \Delta P_{ha}$$

Head Loss Modeling

- Compressibility related to void volume.

$$\beta_v = N P_m^{-b} \quad \text{where } b \approx 1$$

N = material specific parameter

- Therefore, for the first compression:

$$X = X' (P_m / P_m')^{-N} \quad \text{where } X' \text{ void ratio at } P_m' \text{ at start of compression}$$

P_m' mechanical stress at start of compression

- After first compression:

$$\beta_v = N P_{\max}^{-1} \quad \text{where } P_{\max} \text{ highest compressive stress on material}$$

$$X = X(P_{\max}) \exp \left[N - \frac{N P_m}{P_{\max}} \right] \quad \text{where } X(P_{\max}) \text{ void ratio at } P_{\max}$$

Note, the value of N will be determined from test data.

Head Loss Testing

- Project Title: Head Loss Testing
 - Confirmatory head loss testing using typical debris
- Objectives:
 - Characterize PWR sump head loss for insulation and coating debris.
 - Characterize head loss sensitivity to
 - debris bed composition
 - debris distribution in bed,
 - fluid temperature.
 - Design test facility to improve
 - temperature measurement and control,
 - bed thickness measurement,
 - measurement of constituent mass in bed.
 - Provide data to improve head loss calculational method.
- Contractor: Pacific Northwest National Laboratory