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

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# 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<br>**Fiber, Particle or "Unsaturated" Particles in Fiber Bed** | Flow<br>**"Saturated" Particles in Fiber Bed** | Flow<br>**Fibers**<br>**"Saturated" Particles in Fiber Bed** | Flow<br>**Particles**<br>**"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 | ● Best estimate Δp for bed with one debris type<br>● Lower bound Δp for bed with two debris types | ● Best estimate Δp for "saturated" bed with two debris types | ● Upper bound Δp for "unsaturated" bed with two debris types | ● 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

Viscous Term — Kinetic Term

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

  - 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.

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

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

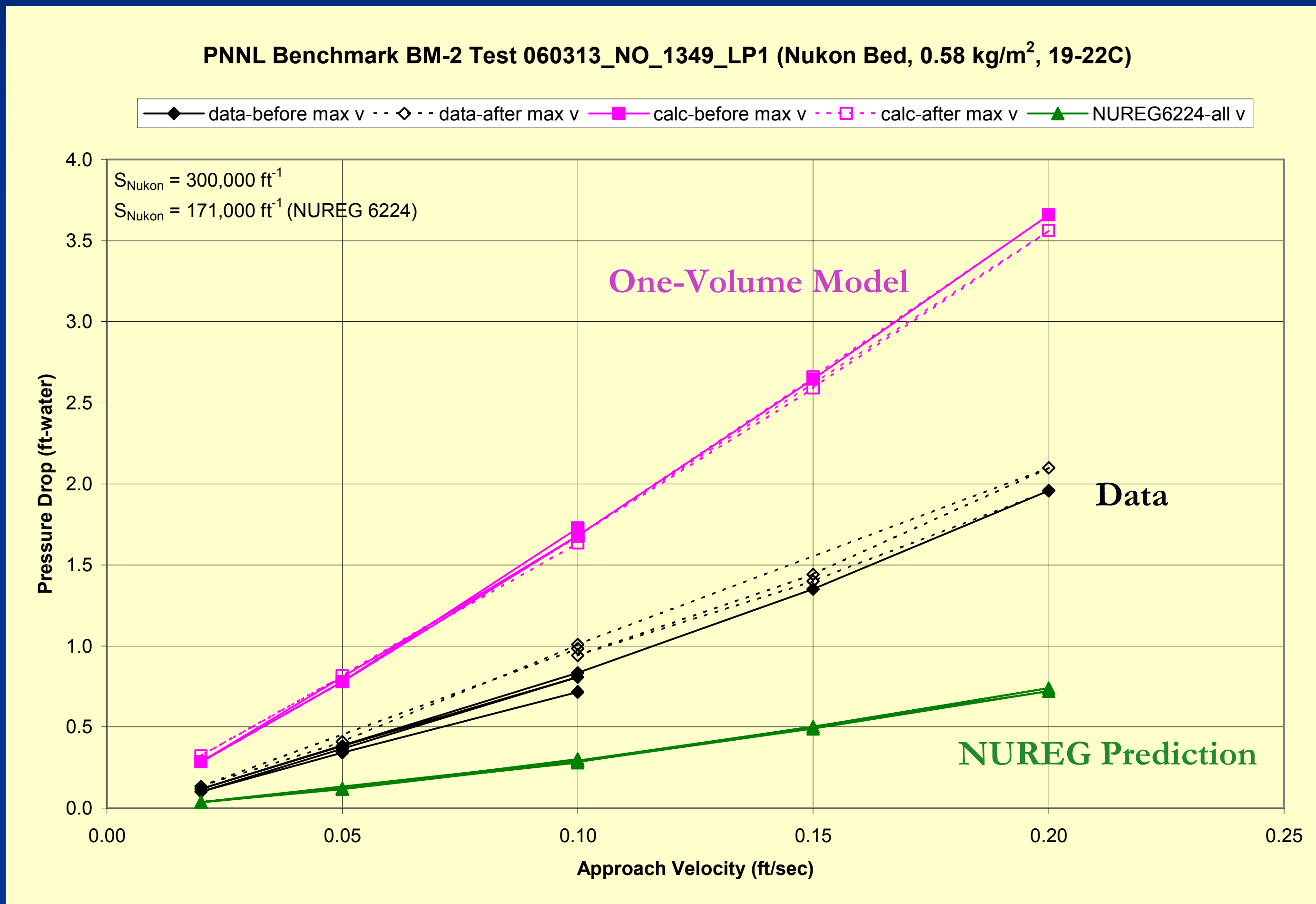
# Information Needed for Calculations

- 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

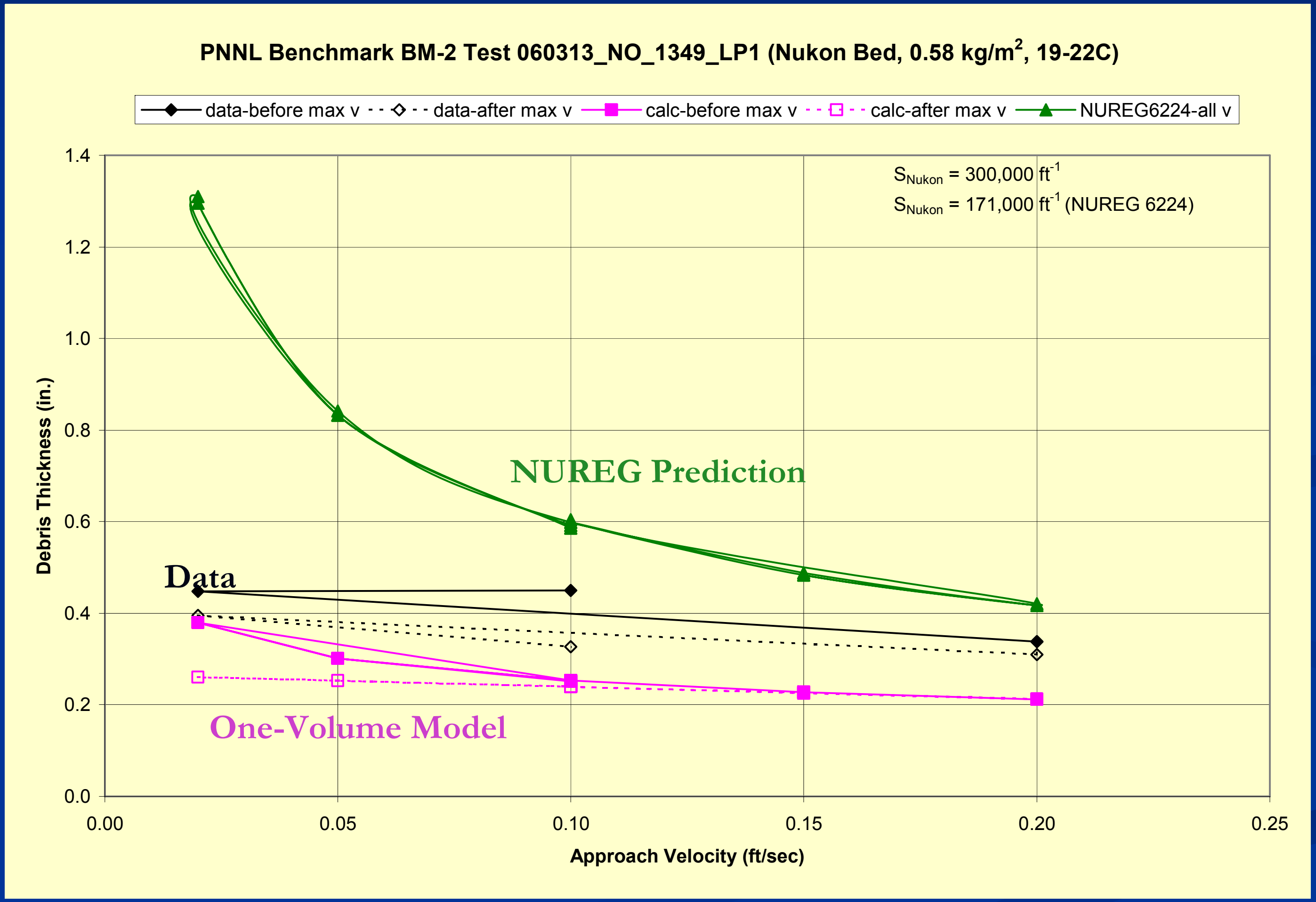
- One-volume Calculations compared to results from
  - PNNL tests
  - ANL tests
  - LANL/UNM tests
- Two-volume Calculations compared to results from
  - PNNL tests
  - LANL/UNM tests

# Pressure Drop for Nukon-Only Test



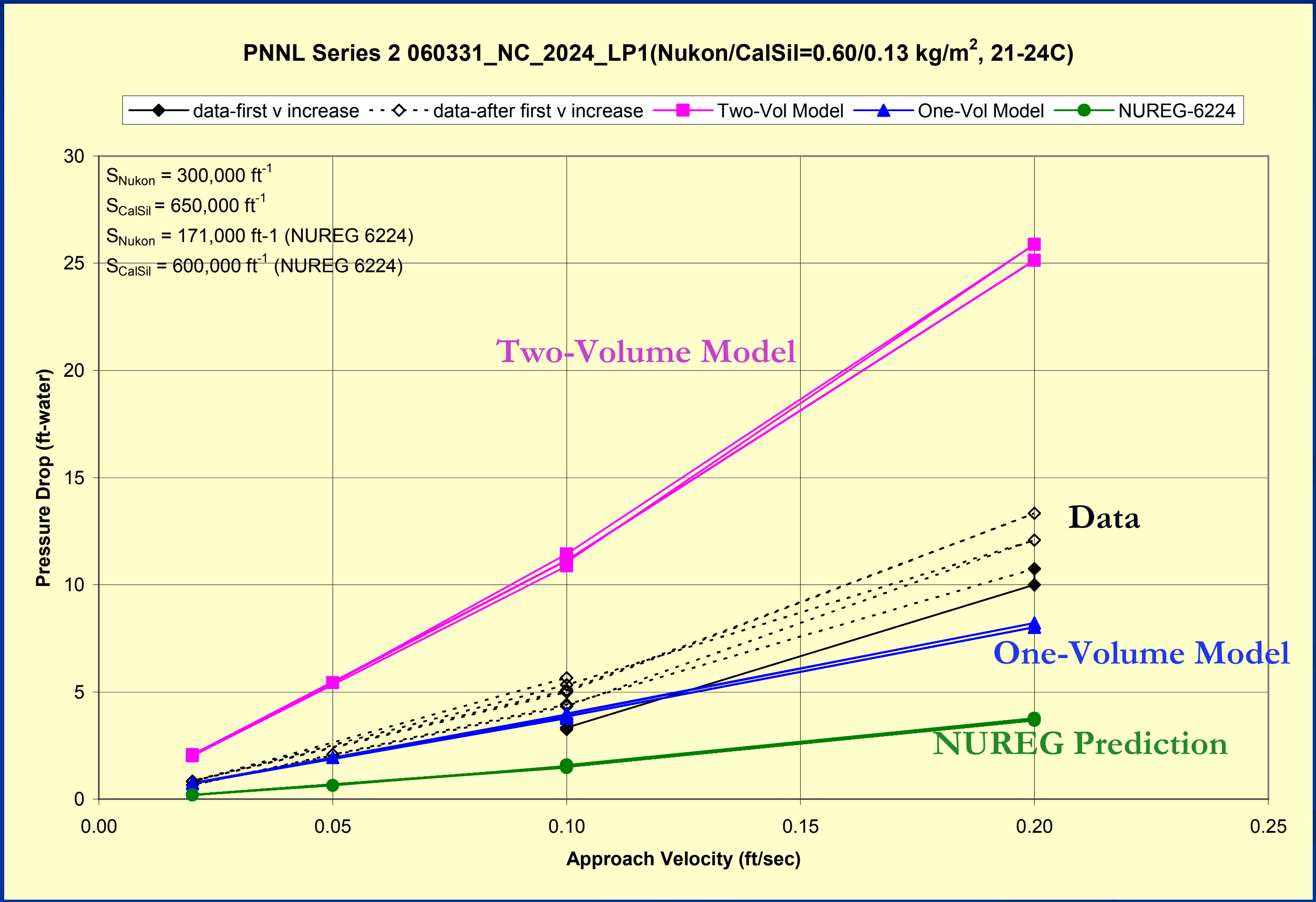

- One-volume predictions are comparative or higher than test data.

# Bed Thickness for Nukon-Only Test



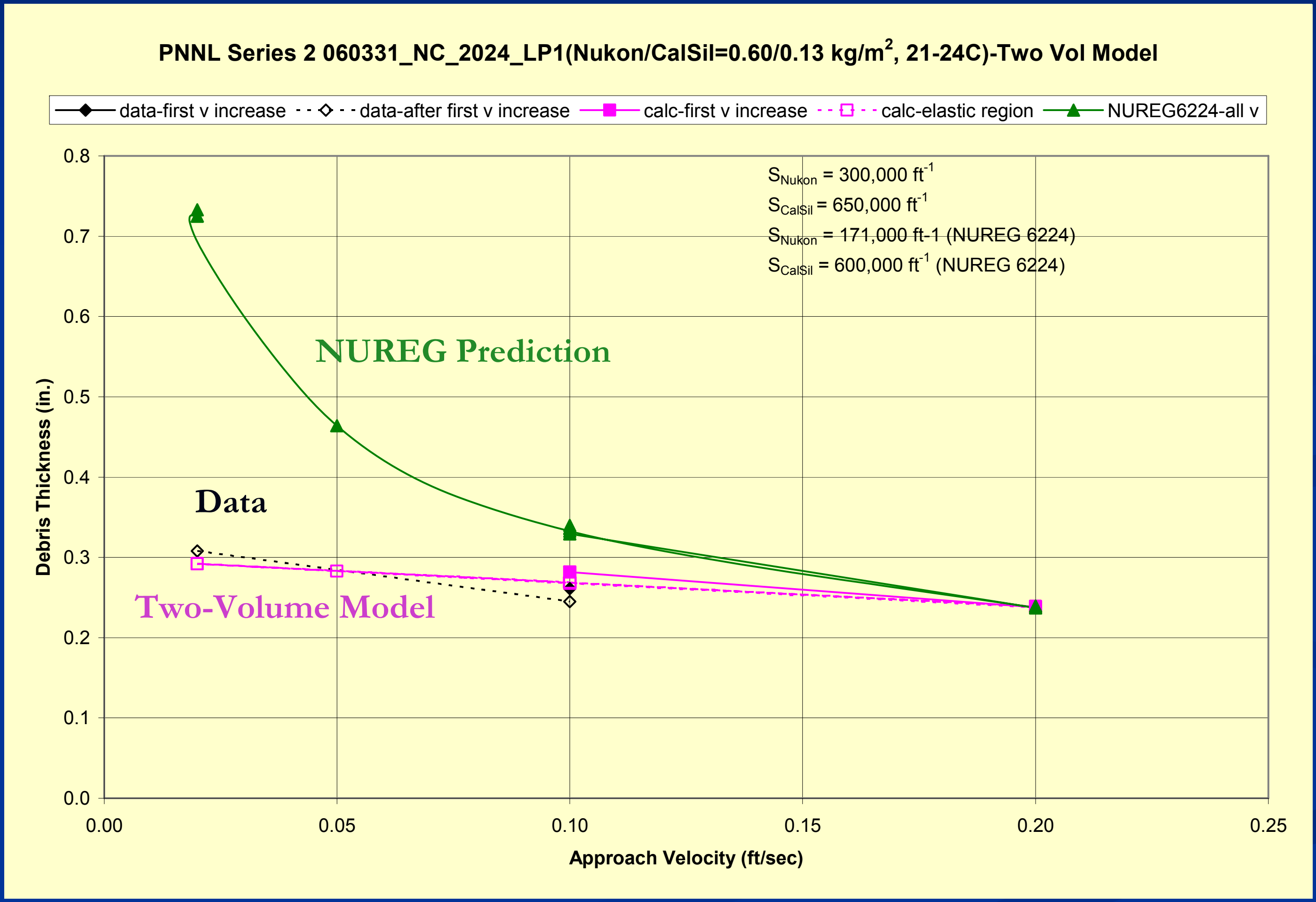

- One-volume predictions are close to test data.

# 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.

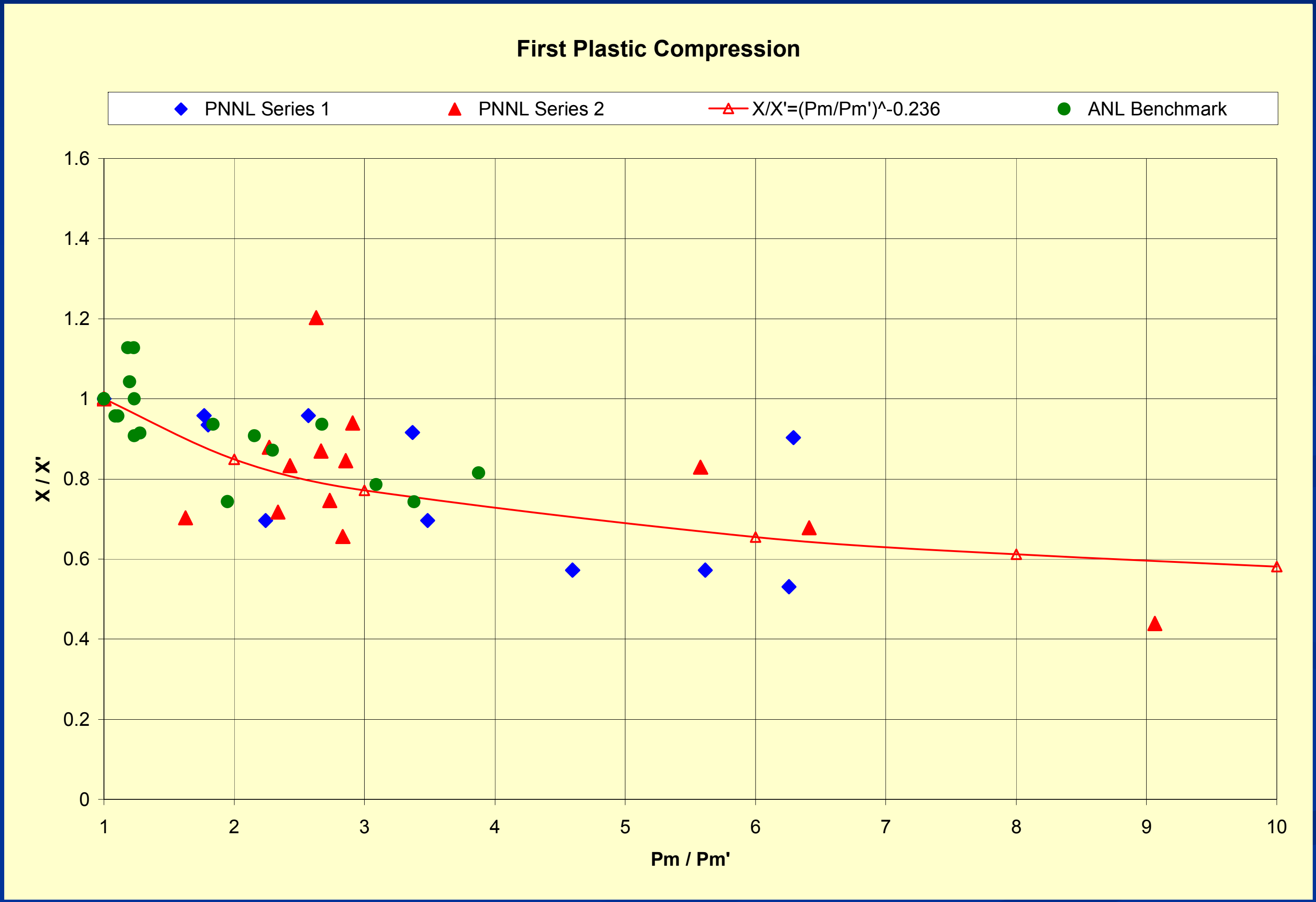
# Conclusions

- 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

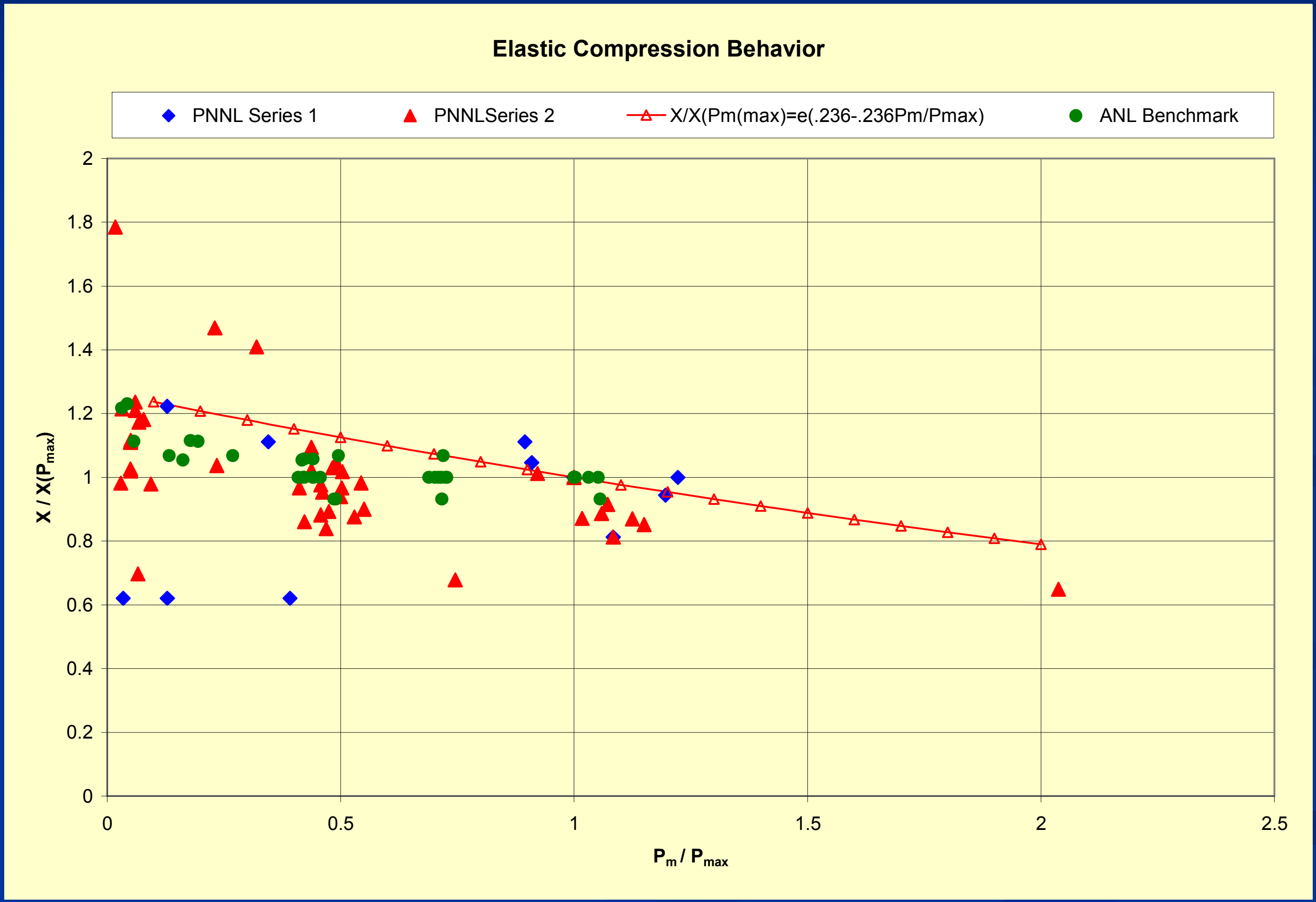
- Backup Slides

# 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.

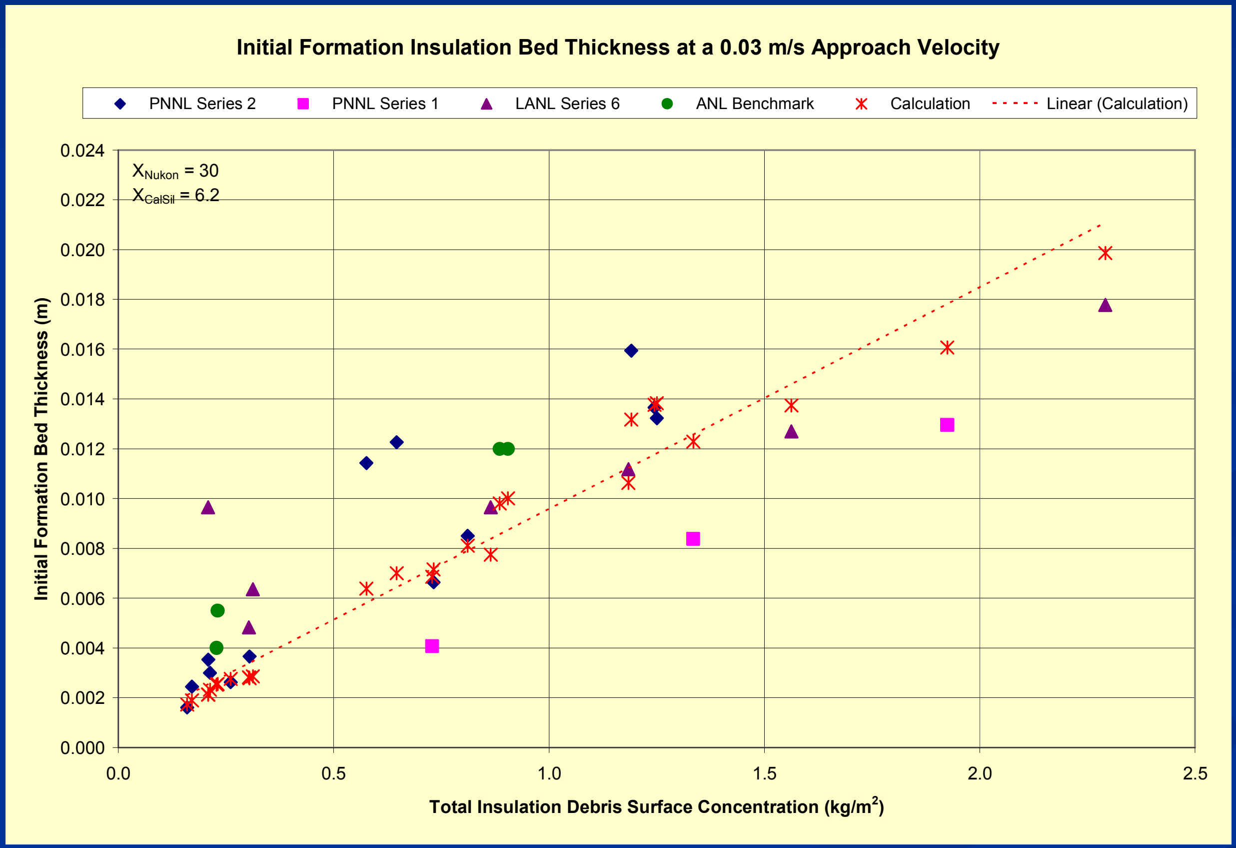
# Head Loss Modeling




- 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.

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

# Information Needed from Testing

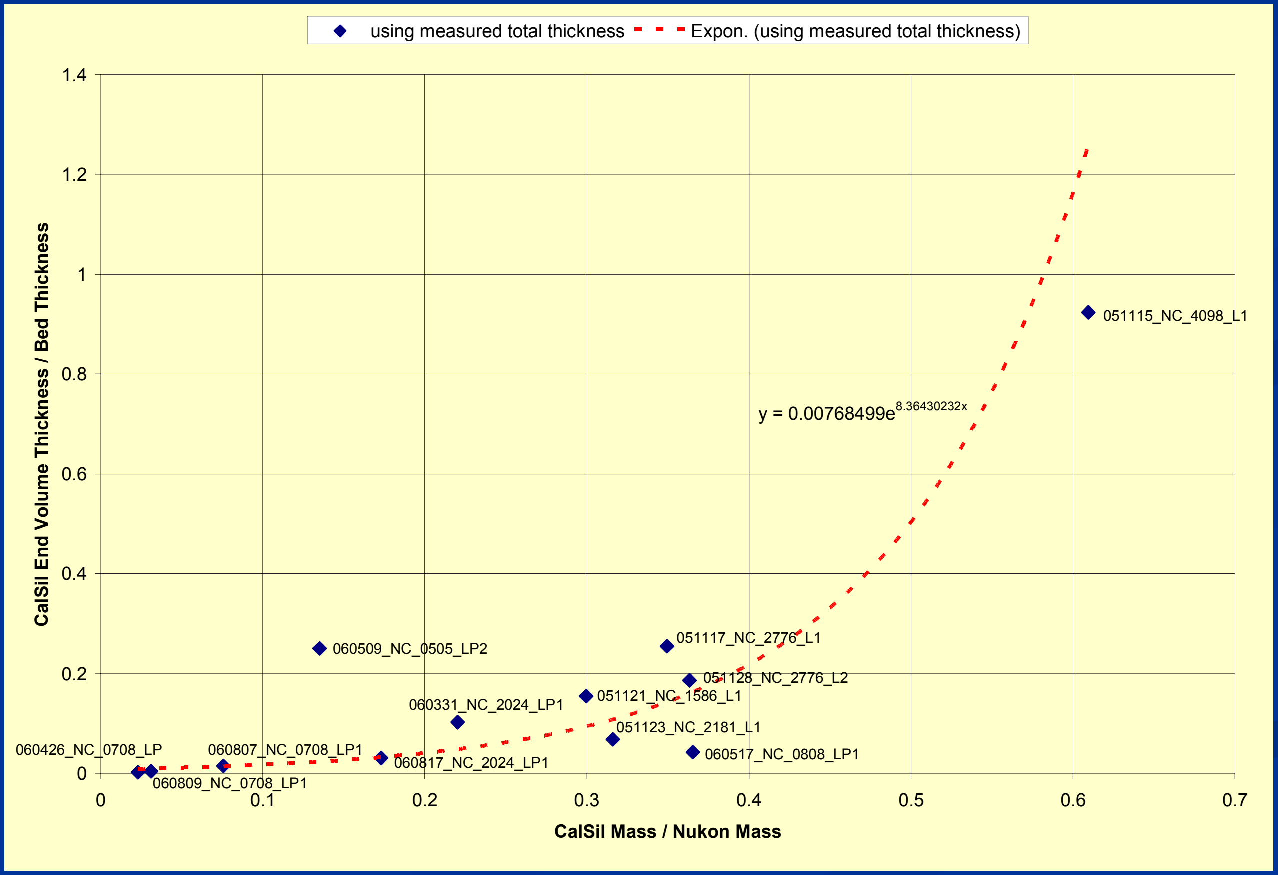
- Actual material masses in debris bed

| 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

Viscous Term　　　Kinetic Term

$$\frac{\Delta p}{L} = \frac{150 \mu V}{D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75 \rho V^2}{D_p} \frac{(1-\varepsilon)}{\varepsilon^3}$$

# Head Loss Modeling

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

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

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

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

# Viscous Term for Pressure Drop

- Using the Kozeny-Carman equation,

$$K = \frac{\varepsilon^3}{k_k S_v^2 (1-\varepsilon)^2}$$

where $k_k$ is the Kozeny constant

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

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

# Viscous Term for Pressure Drop

- If a dimensionless permeability function is defined as:

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

where the void ratio $X = Vol_{void}/Vol_{solid}$

- 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

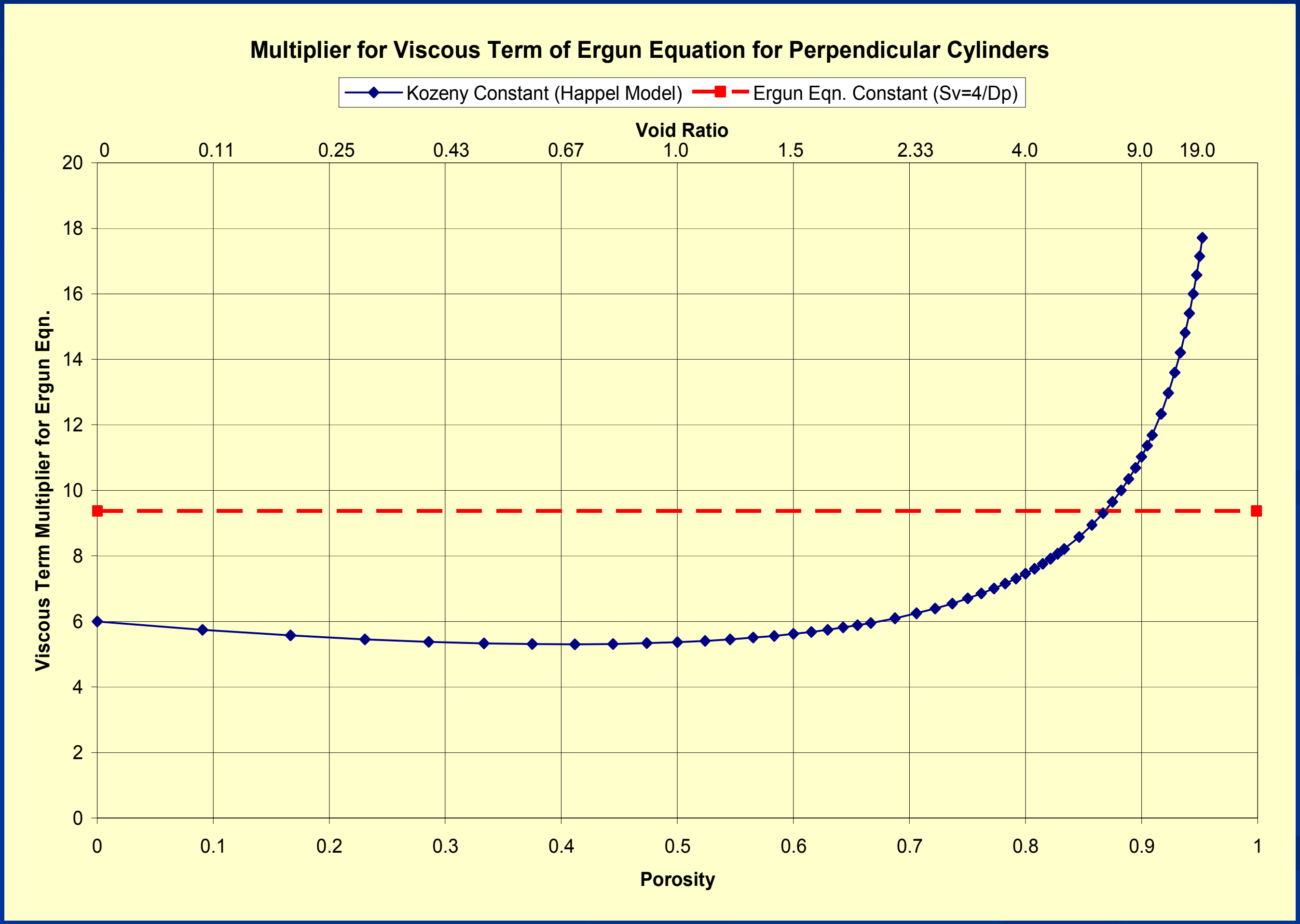
Viscous Term — Kinetic Term

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

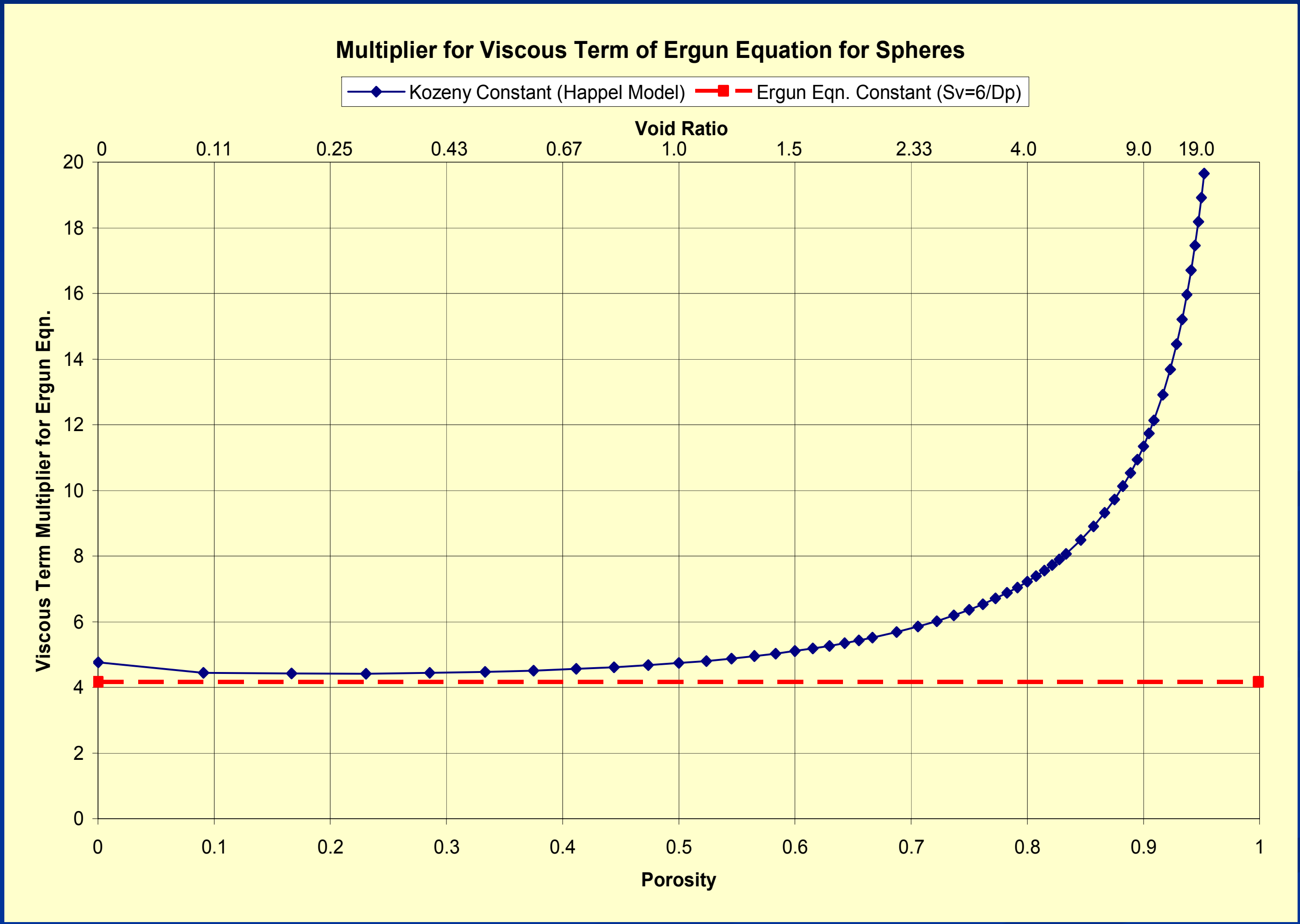
- Head loss equation with viscous term from Darcy equation

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

# Viscous Term for Pressure Drop



# Viscous Term for Pressure Drop



# Kinetic Term for Pressure Drop

- Semi-empirical pressure drop relation

Viscous Term — Kinetic Term

$$\frac{\Delta p}{L} = \frac{a\,\mu\,V\,S_v^{\,2}}{36}\,\frac{(1-\varepsilon)^2}{\varepsilon^3} + b\left[\frac{(1-\varepsilon)\,\mu\,S_v}{\varrho\,V\,6}\right]^c \frac{\varrho\,V^2\,S_v}{6}\,\frac{(1-\varepsilon)}{\varepsilon^3}$$

For plain square type woven metal screens

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

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

For a bed composed of spherical particles

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

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

# Porous Medium Pressure Drop

Viscous Term — Kinetic Term

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

Definitions

- $K(X)$ dimensionless permeability function dependent on debris type
- $\Delta p_{debris}$ pressure drop across debris bed
- $L$ debris bed thickness
- $V$ approach velocity
- $X$ void ratio ($Vol_{void}$ / $Vol_{solid}$)
- $\varepsilon$ porosity ($Vol_{void}$ / $Vol_{total}$)

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

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

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

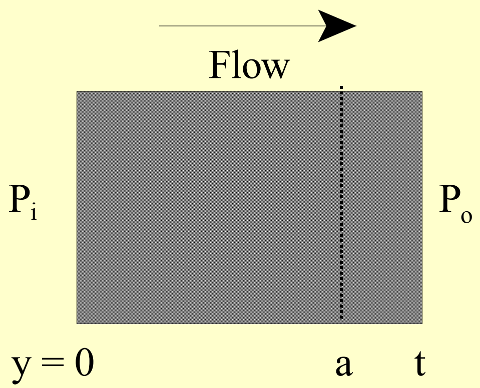
$$\left[ S_{Nukon} \, 1.95 \left[ \frac{(1-\varepsilon_{Nukon}) \, \mu \, S_{Nukon}}{\rho \, V \, 6} \right]^{0.071} \frac{(1-\varepsilon_{Nukon})}{\varepsilon_{Nukon}^3} + S_{CalSil} \, 3.89 \left[ \frac{(1-\varepsilon_{CalSil}) \, \mu \, S_{CalSil}}{\rho \, V \, 6} \right]^{0.13} \frac{(1-\varepsilon_{CalSil})}{\varepsilon_{CalSil}^3}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

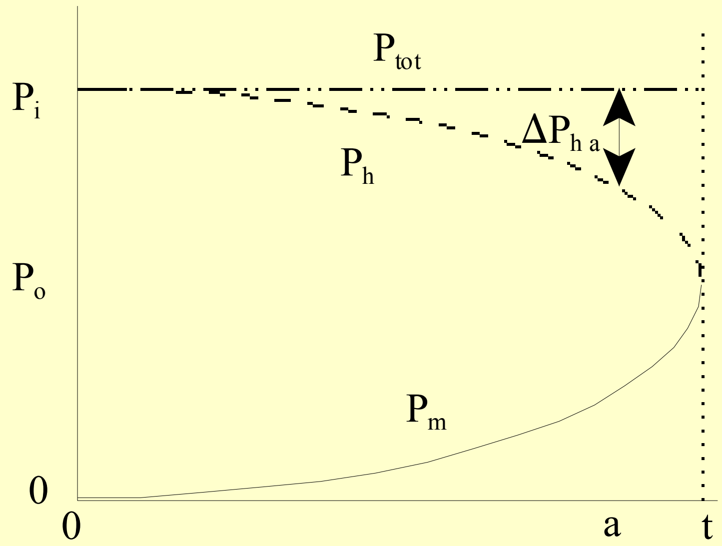
for Nukon with $0.5 < \frac{Re}{(1-\varepsilon)} < 9.85 \times 10^4$ and $0.564 < \varepsilon < 0.919$

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

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

# Head Loss Modeling




$P_{tot} = P_m + P_h$

| | | | |
|---|---|---|---|
| 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.

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

  $N$ = material specific parameter

- Therefore, for the first compression:

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

  $P_m'$ mechanical stress at start of compression

- After first compression:

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

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