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GSI-191 Test Program Summary

Scaled Head Loss Testing

NRC Visit

February 26, 2015

Agenda

- Subscale Test Facility Parametric Tests
- Full-Area FA Testing
- Summary of Results – Final Limits

Subscale Test Facility Parametric Tests

Subscale Loop Testing

- Purpose: Provide test data that supports the development of higher fibrous debris loading acceptance criteria
  - Examine effects of parametric variation
  - Addresses limits and conditions in the NRC SE (WCAP-16793-NP-A Rev 2)
  - Addresses ACRS concerns
- Experimental Objective: Determine the relative importance of the following variables on debris bed head loss:
  - Flow Rate
  - Debris Concentration
  - Water Chemistry (pH and buffer type)
  - Particulate Size and Distribution
  - Capture Geometry
    - Grid (fuel rod diameter and subchannel pitch)
    - Core Inlet
  - Fiber Size and Distribution
  - Particulate-to-Fiber Ratio (p:f)

Parametric Tests – Round 1

- 23 Test Series Completed
  - 95 Independent Tests
  - Broken into 2 Phases
- Phase 1 Testing
  - Shakedown Facility
  - Determine baseline condition for parametric studies
  - Flow rate variation study
  - 9 Test Series / 36 Independent Tests
- Phase 2 Testing
  - Parametric Studies
  - 14 Test Series / 59 Independent Tests

Parametric Test Matrix

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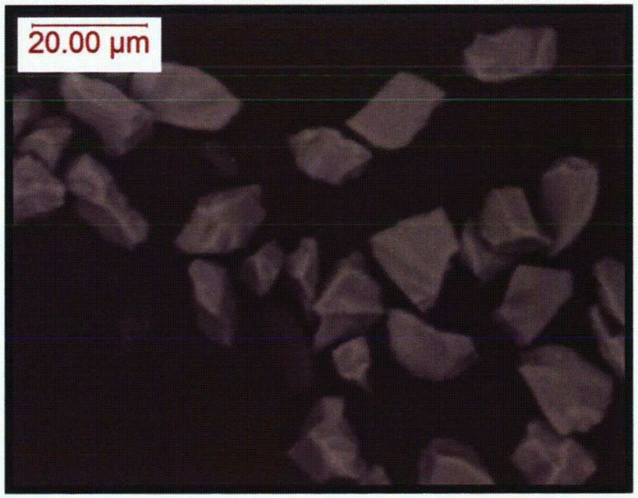
Test Series	Flow Rate (gpm)	Fiber Loading (g)	Debris Injection Time (min)	p:f Ratio	pH	Buffer Type	Particulate Size	Grid Type
10	8.2	25	30	10:1	7	NaOH	A	RFA
2	2.67	25	30	10:1	7	NaOH	A	RFA
11	11.5	25	30	10:1	7	NaOH	A	RFA
13	8.2	25	300	10:1	7	NaOH	A	RFA
9	8.2	25	30	0:1	7	NaOH	A	RFA
3	8.2	25	30	1:1	7	NaOH	A	RFA
14	8.2	25	30	15:1	7	NaOH	A	RFA
11	8.2	12.5	30	10:1	7	NaOH	A	RFA
14	8.2	12.5	30	30:1	7	NaOH	A	RFA
19	8.2	25	30	10:1	9	NaOH	A	RFA
20	8.2	25	30	10:1	7	TSP	A	RFA
21	8.2	25	30	10:1	7	NaTB	A	RFA
16	8.2	25	30	10:1	7	NaOH	B	RFA
17	8.2	25	30	10:1	7	NaOH	C	RFA
18	8.2	25	30	10:1	7	NaOH	D	RFA
12	8.2	25	30	10:1	7	NaOH	A	HMP
22	8.2	25	30	10:1	7	NaOH	A	UFA
23	8.2	25	30	10:1	7	NaOH	A	OFA

Subscale Parametric Test Conclusions

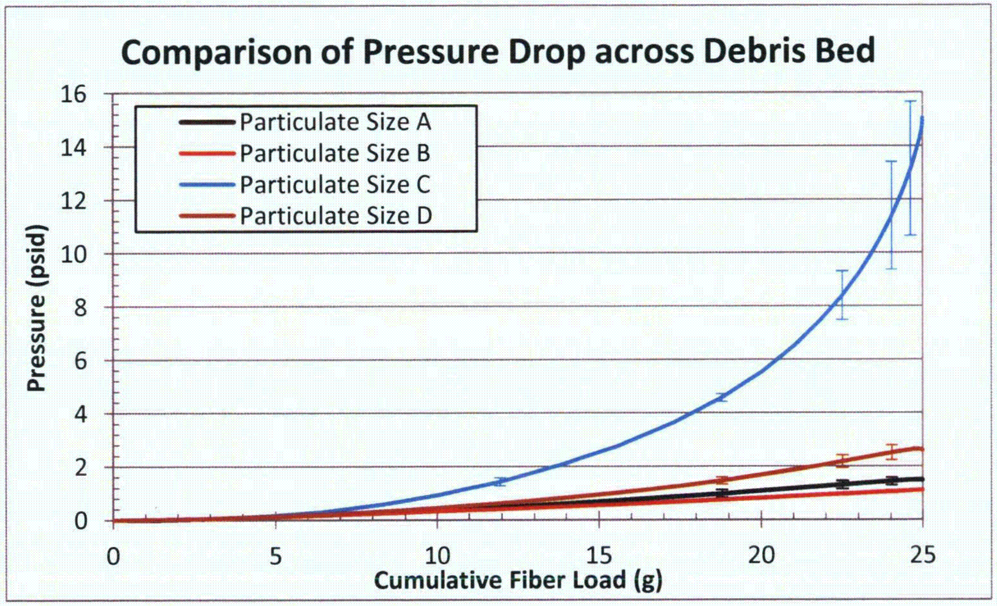
- Most important contributors include flow rate, p:f ratio and particulate size
  - Higher flow rates more limiting (as expected)
  - Higher p:f ratios more limiting (as expected w/o chem effect)
  - For the conditions tested, increasing particulate size results in a higher pressure drop across the debris bed
- Inputs having a small impact include:
  - pH
  - Grid geometry
  - Buffer
- Inputs not found to be significant include:
  - Debris Concentration / Injection Rate

Subscale Test Results – Round 2

- Round 2 Testing Began 06/02/2014
  - Focus on Particulate Size and p:f Ratio
  - Objectives
    - Determine an appropriate particulate size distribution for final debris limit tests.
    - Determine the influence of p:f ratio and use that information to formulate a strategy for addressing particulate load in the final limits.
  - 43 additional tests
    - Silicon Carbide used as Particulate Surrogate
    - Particulate Sizes up to 72 μm Tested
    - W-RFA Grid



Subscale Particulate Size and Distribution Results



Type A: 10µm mean diameter

Type B: 6 µm mean diameter

Type C: 17 µm mean diameter

Type D: uniform mix of A,B and

- The pressure drop is shown to be sensitive to the particulate size.
  - Larger particles tend to capture in the debris bed more readily.

Subscale Particulate Size and Distribution Results

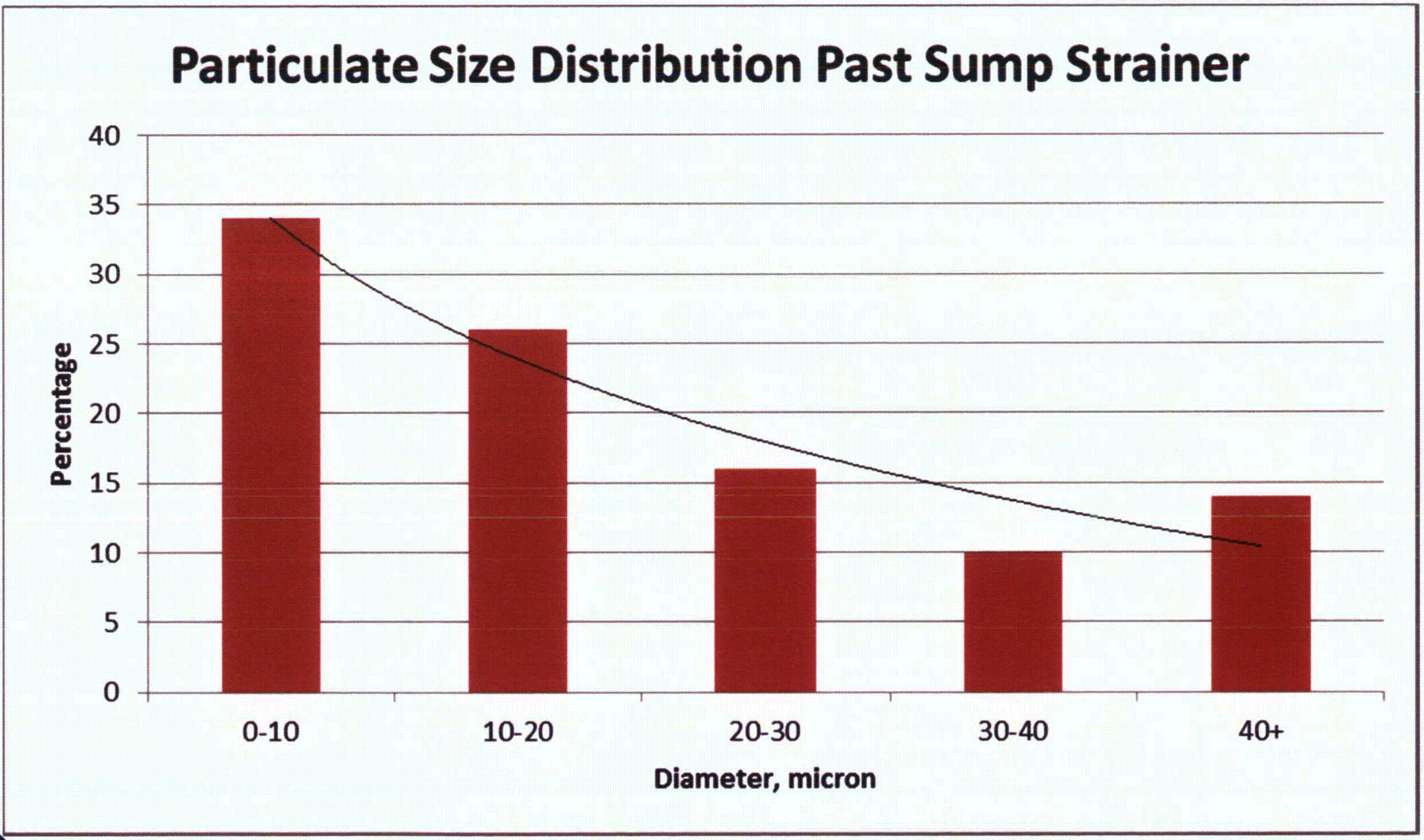
- Filter Bag results can be used to determine the capture efficiency of particulates as a function of mean diameter.
- Results show that the capture efficiency increases with increasing particulate size.
- The hypothesis is that larger particulate tend to capture in the bed more efficiently. This reduces the bed porosity resulting in higher pressure drops.
- At these particulate sizes, packing factor appears to be less important

Mean Particulate Diameter (μm)	Average particulate Penetration Mass (g)	Particulate Capture Efficiency (%)	Bed Pressure Drop (psid)
6.3	244.99	2.0	1.1
10.4	233.90	6.4	1.5
16.95	174.69	30.1	15.1

Subscale Particulate Size and Distribution Results

- Estimates from packing of non-spherical particles (i.e. fiber strands) indicate that near 100% filtration efficiency will occur at a particulate size of >55 μm
  - Above 100% filtration efficiency, the dP will stabilize or begin to decrease
  - This defines the maximum particulate size that should be tested
  - Subscale testing was done to confirm
- – Since it is not expected that any single size of particulate will exclusively arrive at the fuel inlet, some distribution of particulate size needs to be defined
  - Previous work for GSI-191 has suggested that a uniform distribution be considered
  - Filter bag results from subscale testing and plant strainer test data suggest that the distribution is weighted toward smaller particulates

Subscale Particulate Size and Distribution Results

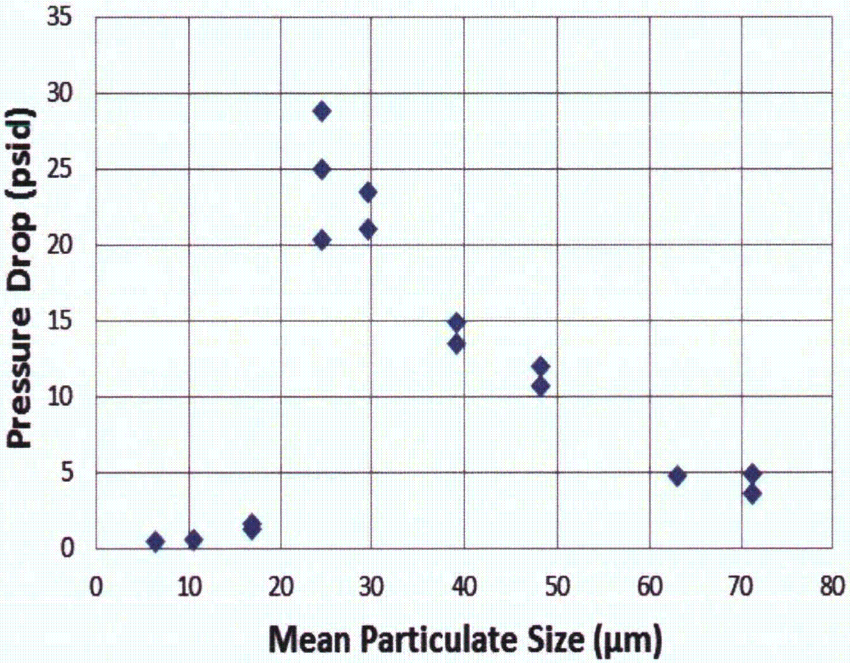


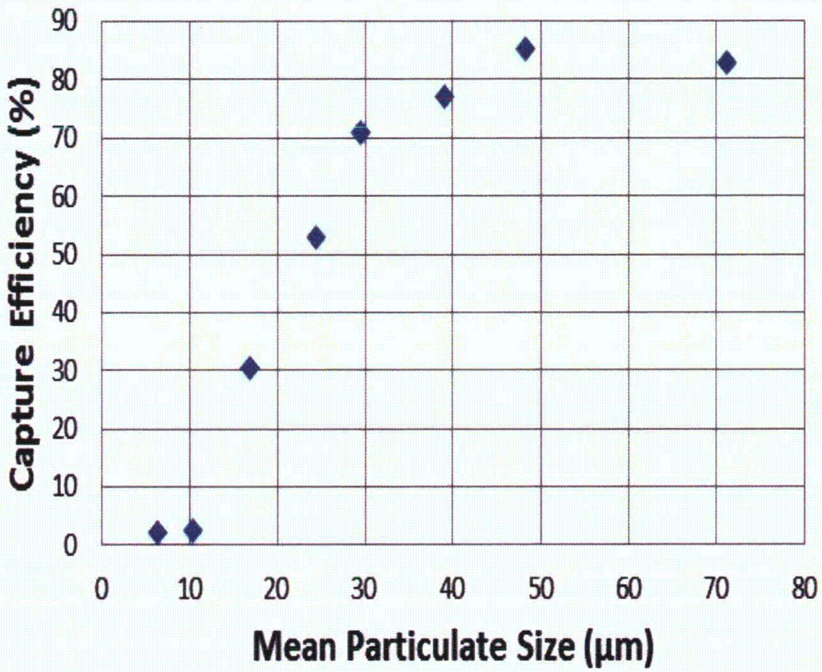
Subscale Testing – Particulate Size

- Prototypically, a broad range of particulate sizes are expected to penetrate the sump strainer.
  - Strainer test data supports this assertion.
  - Test Strategy
    - Determine the particulate size that results in the highest dP.
    - Define a particulate size distribution that ends at the limiting particulate size
      - Follows a distribution consistent with available strainer penetration data.

Particulate Size Test Results

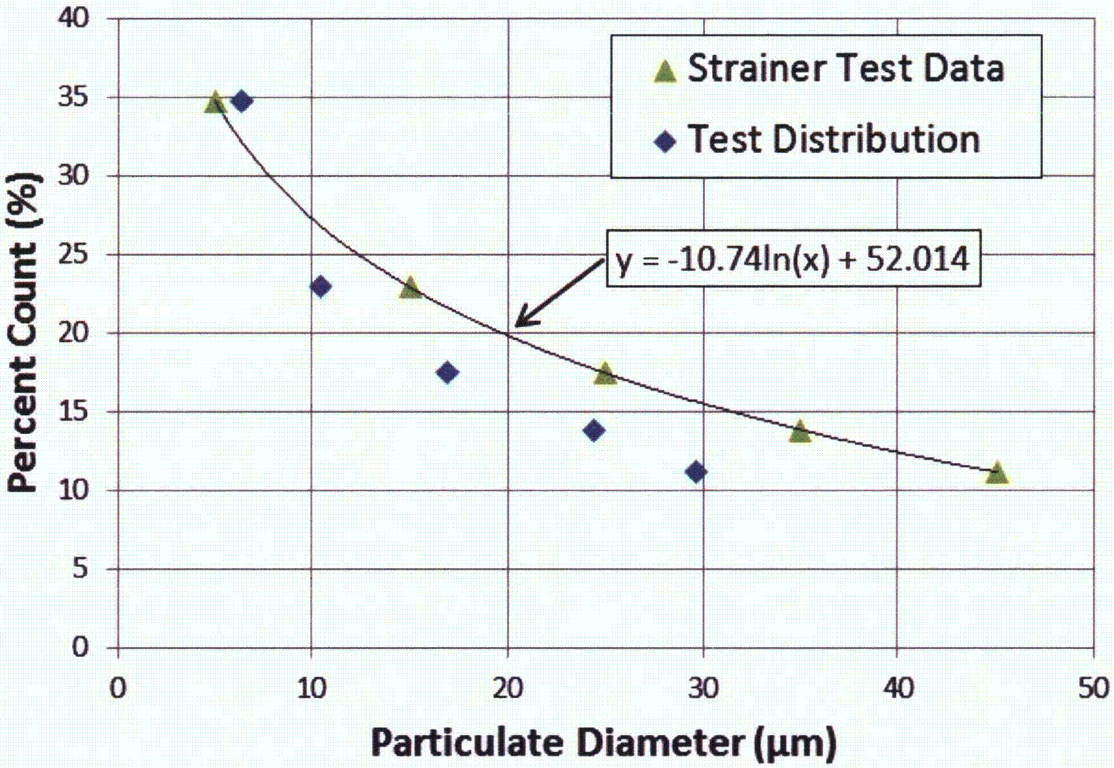
Fiber: 56 g/FA, p:f Ratio: 10:1, 36.7 gpm/FA





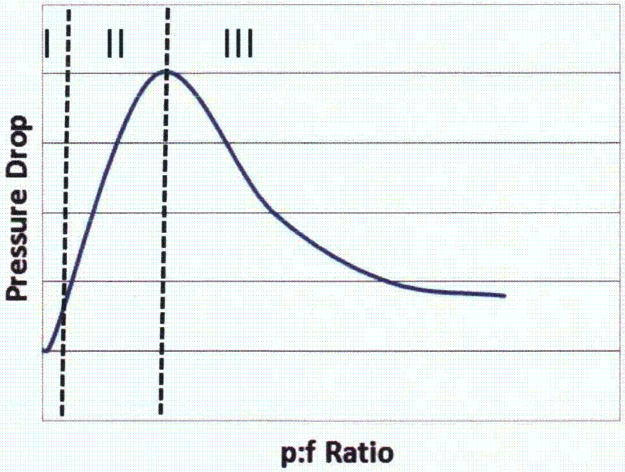
- 24 µm particulate create highest dP
- Particulates larger than 50 µm captured at > 80% efficiency

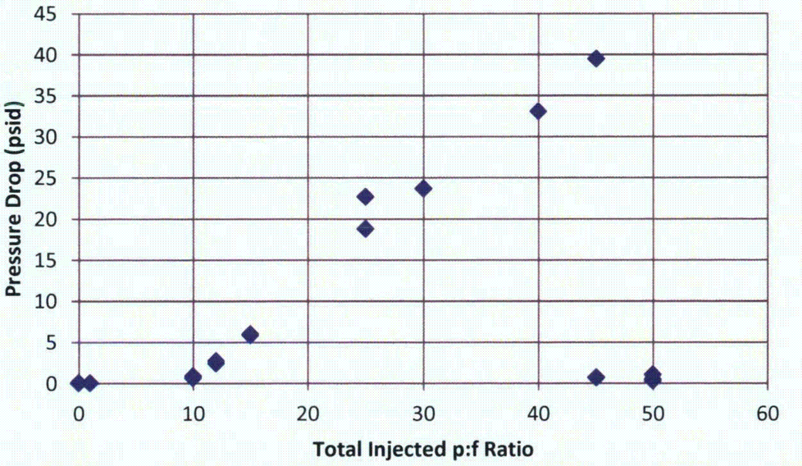
Determination of Size Distribution



p:f Ratio Study with Particulate Size Distribution

- p:f ratio testing was done using the newly defined particulate size distribution.
- Results indicate that the bed behaves very differently depending on p:f ratio.
- Three "Regimes" Identified
  - Regime I – Stable Fiber Dominated Debris Bed
  - Regime II – Stable Particulate Dominated Debris Bed
  - Regime III – Unstable Particulate Dominated Debris Bed





Subscale Conclusions

- Additional Testing
  - Prototypical Core Inlet Geometry
  - AFP hole size/geometry testing
  - Final Limits

Full-Area FA Testing

Full-Area FA Testing

- Original intent of PA-SEE-1090 was to test in two stages:
  - Subscale Facility to do parametric studies and define small set of conditions that provided limiting pressure drop
  - Full-Area Facility to do final limits testing using the inputs from the Subscale Facility
- After 139 tests performed in the Subscale Facility, a review of the results indicates that full-area FA testing is not necessary
- Basis for decision:
  - Fidelity/repeatability of subscale tests
  - The scaling of the Subscale Facility adequately represents a full-area fuel assembly with acceptable distortion
  - Trending of subscale results agrees with pressure drops from full-area FA testing done for WCAP-16793-NP, Rev. 2

Head Loss Scaling

- As part of the subscale facility design process, a scaling analysis was performed to:
  - Determine subscale facility dimensions and test conditions such that the dominant physical processes are preserved.
  - Define necessary scaling ratios such that the subscale results can be translated to the prototypic system and the analytical model.
- A bottom-up, dimensional scaling analysis is performed that focuses on debris bed formation and the resulting pressure drop across the bed.
  - Four dimensionless scaling groups are defined and priority is placed on the inertial loss term associated with flow through a packed bed.
  - Debris material similitude is assumed.
  - The impact of fluid temperature, flow rate, and channel geometry are considered.

Head Loss Scaling

- A summary of the dimensionless groups is shown below:

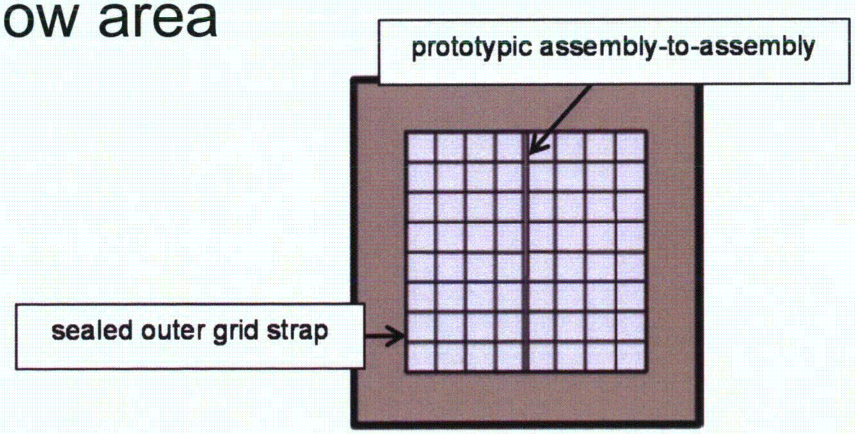
Scaling Group	Definition	Ratio (Subscale:FA)	Distortion (%)
$\mathrm{Re}^* = \frac{\rho_f \vartheta_p d_p U}{\mu_f (1-\varepsilon)}$	$\frac{viscous\_forces}{inertial\_forces}$	1:1	0
$Ga^* = \frac{\rho_f^{\,2} g \vartheta_p^{\,3} d_p^{\,3} \varepsilon^3}{\mu_f^{\,2} (1-\varepsilon)^3}$	$\frac{viscous\_forces}{bouyancy\_forces}$	1:1	0
$\mathrm{Re} = \frac{\rho_f d_h U}{\mu_f}$	$\frac{viscous\_forces}{inertial\_forces}$	0.917:1	-8.3
$St = \frac{\tau_p}{d_h / U}$	$\frac{fluid\_response\_time}{particle\_response\_time}$	1.091:1	9.1

Subscale Facility Geometric Scale

- Assembly to Assembly Gap
  - Gaps formed between adjacent assemblies installed in a PWR core result in long narrow gaps, that are approximately 0.04 in wide, and gap intersections that may affect debris bed morphology and the resulting head loss.
  - Previous testing simulated this gap with the FA centered in the test vessel with a ½ gap around the periphery
    - Wall boundary condition instead of a symmetry condition which was an unevaluated distortion
    - The capture geometry near the edge did not provide a ledge for debris capture
  - Based on these observations, the Subscale Facility uses a prototypic gap which is centered in the test vessel.

Subscale Facility Geometric Scale

- Assembly to Assembly Gap
  - Need to maintain the gap with and an appropriate flow area to gap ratio
  - For a W 17x17 FA, the ratio of gap area to FA pitch is $[(8.466)^2-(8.466-0.04)^2]/(8.466)^2$, or 0.94% of the total FA area occupied by the gap
  - In the subscale facility, the ratio of the gap area to the test section footprint is $1- (4^2 – 0.04*4)/4^2$, or 1% of the subscale facility flow area



Subscale Facility Geometric Scale

- Thimble and Instrument Tubes
  - Fuel assemblies consist of an array of fuel rods, instrument tubes, and thimble tubes all with various diameters.
  - The subscale rod bundle consists of two 4x8 grid sections with a gap separating the sections. Each grid section contains a combination of thimble tubes, instrumentation tubes and fuel rods.
  - The ratio of these components to a full-area fuel assembly is compared to ensure that the Subscale Facility adequately represents a full-area fuel assembly.
    - For a W 17x17, the ratio of thimble and instrument tubes to fuel rods is 0.095
    - In the Subscale Facility, the ratio of thimble tubes to fuel rods is 0.103

Subscale Facility Geometric Scale

- Thimble and Instrument Tubes
  - To evaluate this impact on debris bed head loss, the appropriate dimensionless parameter is the percent open flow area.
    - Considering only the rods themselves and neglecting the gap formed between assemblies, the percent open area for a 17x17 RFA assembly is 52.7%
    - For the Subscale Facility, the percent open area is 52.6%
  - Therefore, the effect of this potential distortion is negligible

Subscale Facility Geometric Scale

- Hydraulic Diameter
  - PWR's have open lattice cores and there is no wall between assemblies.
  - However, in a full-area fuel assembly test there would be a wall around the periphery of the assembly.
  - Therefore, the Subscale Facility hydraulic diameter is assessed against a fuel assembly that is surrounded by a flow column.
  - The full-area FA hydraulic diameter is 0.399 in
  - The Subscale Facility hydraulic diameter is 0.366 in
  - The hydraulic diameter ratio is then 0.917

Subscale Facility Geometric Scale

- Fiber and Particulate Mass
  - Debris limits are currently reported on a single FA basis
  - As described above, the edge effects, gap between FAs, and grid geometry are appropriately represented in the Subscale Facility
  - Therefore, the debris load in the Subscale Facility are directly relatable to a full-area FA using the flow area ratio, which is 0.233
  - For example, 3.5 g of fiber in the Subscale Facility would equate to 15 g of fiber in a single FA

Scaling - Conclusions

- The scaling analysis completed above demonstrates that the Subscale Facility is comparable to a full-area fuel assembly in terms of distortions related to pressure drop across a debris bed.
- It has been shown that
  - the geometric scale of the Subscale Facility has negligible distortion when compared to a full-area fuel assembly.
  - the dominant physical phenomena expected to drive debris bed head loss are reasonably preserved.
- Therefore,
  - Using the flow area ratio between the subscale and a full-area fuel assembly it is possible to relate the subscale debris loading to that of a full-area fuel assembly.
  - It is also possible to relate the subscale flow condition to that of the full-area fuel assembly using the same flow area ratio.

Confirmation of dP Trends

- Numerous tests have been performed in the subscale test facility
- Variations in input include
  - Fibrous and particulate debris mass
  - Initial particulate-to-fiber (p:f) ratio
  - Flow rate (velocity)
  - Particulate size
- Results include
  - Pressure drop (dP) across debris bed
  - Amount of fiber and particulate in debris bed
- To better understand the debris bed morphology and behavior of the bed under a variety of conditions, a semi-empirical model was developed to represent subscale data

Description of Model

- The pressure drop model for flow through the debris bed takes the general form defined for flow through compressible porous media:

$$\frac{\Delta P}{L} = AU + BU^2 \qquad \text{(Eq. 1)}$$

- Where

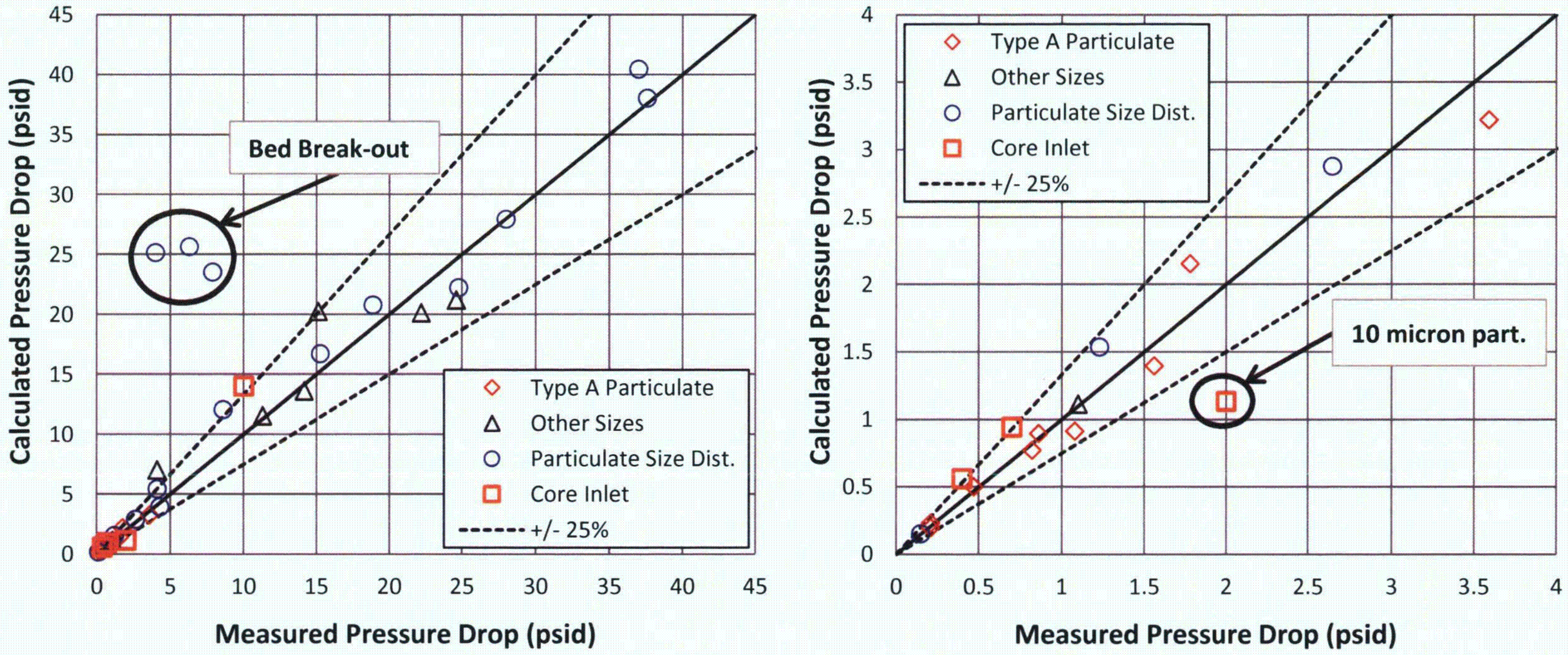
AU	= viscous energy loss term
BU^2	= inertial energy loss term
U	= superficial velocity
ΔP	= hydraulic pressure across a layer of porous media of length L
A, B	= constants dependent on the fluid properties of the flow and the media composition

Description of Model

Description of Model

Description of Model

Comparison of Model Predictions to Experimental Data



Prediction of FA Head Loss

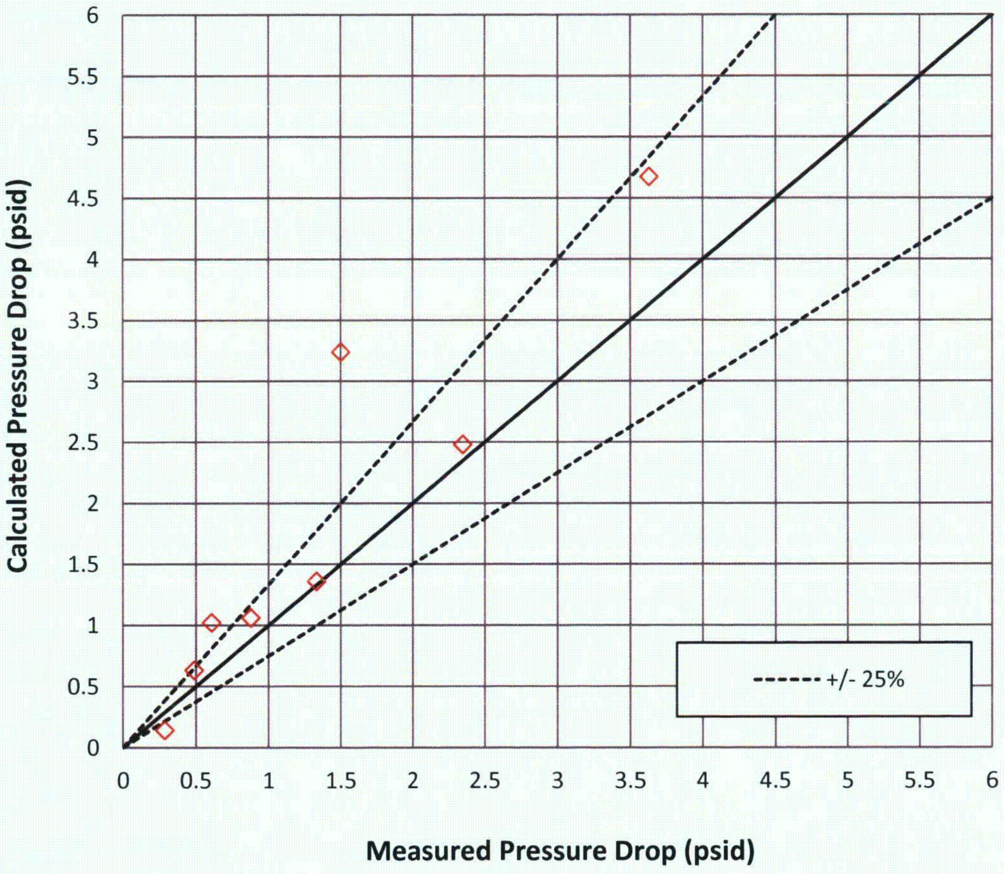
- The model described above is used to predict various results from the WCAP-16793-NP, Rev. 2 test program
- Tests from both the W and CDI test facility were selected
  - Covered a range of flow rates and conditions
  - Developed a single debris bed
- An over-prediction of the pressure drop provides a clear indication that the results from the Subscale Facility are conservative relative to a full-area FA test.

WCAP-16793-NP, Rev. 2 Tests Selected

Test ID	Flow (gpm)	Particulate Load (g)	Fiber Load (g)	P:F Ratio	Assembly Pressure Drop (psid)	Test Location
9-FG-FPC	44.7	20	20	1:1	1.33	CDI Test
12-FG-FPC	44.7	15	15	1:1	0.61	CDI Test
CID22	3	0	75	0:1	0.29	W Test
CID23	3	75	75	1:1	0.49	W Test
CID42	15.5	50	50	1:1	2.35	W Test.
CID49[1]	44.7	25	25	1:1	3.63[1]	W Test.
W-Cross	44.7	25	25	1:1	1.5	CDI Test
AREVA-Cross	44.7	25	25	1:1	0.88	CDI Test

Note 1: Two debris beds were formed during this test. One bed formed at the P-grid/bottom nozzle and the second bed formed at the first mechanical grid. The total debris load from the tests was approximated to be an even split between the two bed locations and the assembly pressured drop listed in the table is that measured across the P-grid/bottom nozzle.

Results of Predictions



Conclusion

- Full-Area FA testing is not necessary
  - Fidelity/repeatability of subscale tests
  - The scaling of the Subscale Facility adequately represents a full-area fuel assembly with acceptable distortion
  - Trending of subscale results agrees with pressure drops from full-area FA testing done for WCAP-16793-NP, Rev. 2
- Therefore, Subscale Facility will be used to determine the final debris limits
- However, core inlet geometry still needs to be evaluated

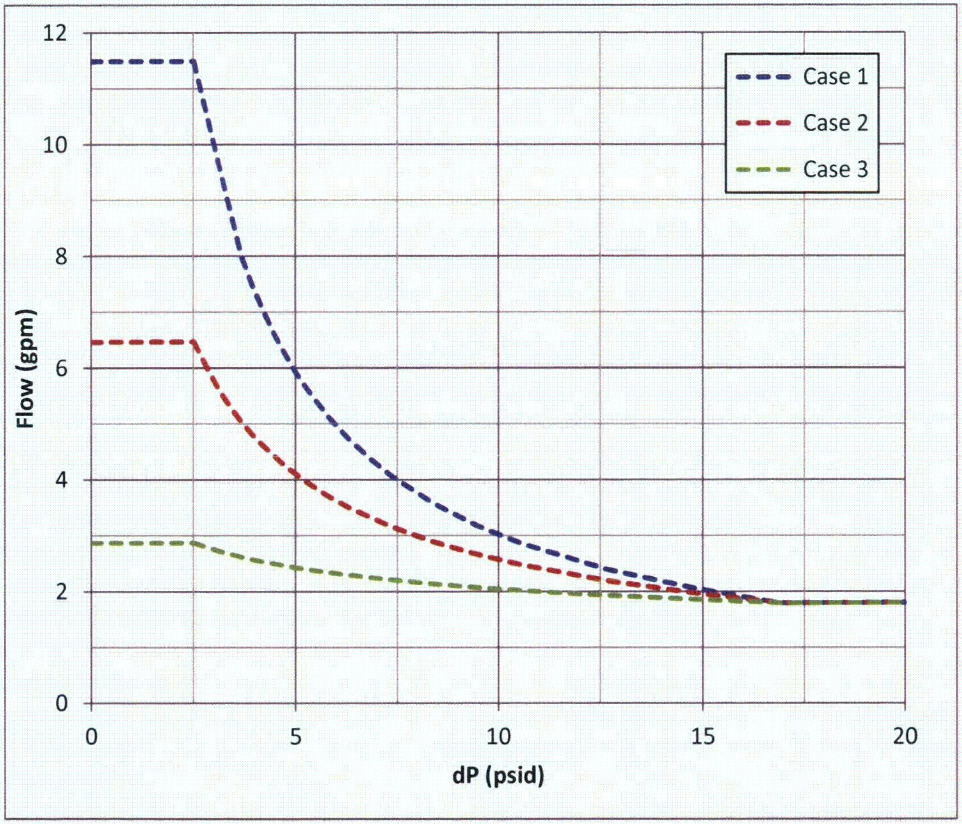
Summary of Results – Final Limits

Additional Subscale Testing

- Testing with core inlet geometry
  - Determine effect of core inlet geometry
    - Westinghouse 17x17 bottom nozzle/P-grid combination tested
  - Particulate size Distribution 1
  - p:f ratio varied to determine limiting value
  - Range of flow rates examined
  - Range of fiber loads examined

Core Inlet Geometry Tests

- Changed flow control to replicate behavior seen in the TH analyses.



Comparison of Results

- Limiting results for W bottom nozzle/P-grid geometry obtained at
  - Low flow rate
  - p:f = 12:1
- Limiting results for single spacer grid geometry obtained at
  - High flow rate
  - p:f ~ 40:1
- Therefore, the fuel entrance geometry plays a role in the debris bed formation and resulting pressure drop
  - Due to bed morphology and resulting capture efficiency

Path Forward

- Since entrance geometry plays a role in the final dP, additional work to evaluate other entrance geometries is needed
  - Will specifically test Areva FUELGUARD/HMP 17x17 fuel design
  - Other entrance geometries that are sufficiently similar to 17x17 W bottom nozzle OR 17x17 Areva FUELGUARD designs to be covered by the testing

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