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Title: Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow StrainerTM Test Data

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Los Alamos
NATIONAL LABORATORY

Technical Review of Selected Reports on Performance Contracting, Inc. Sure-Flow Strainer™ Test Data

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1.0 INTRODUCTION

1.1. Background

Based on the conclusions of the US Nuclear Regulatory Commission study documented in NUREG/CR-6224 [Ref. 1], plugging of emergency core cooling system (ECCS) strainers by loss-of-coolant-accident (LOCA)-related debris is a potential safety issue for boiling water reactors (BWRs). To address this safety issue, Performance Contracting, Inc. (PCI) developed and tested two prototype stacked-disk strainers. Referred to commercially under the trademark Sure-Flow strainer, the PCI strainer concept consists of a stack of coaxial, perforated metal plate disks that are welded to a common perforated, internal core tube. This design maximizes the surface area of the perforated plate while keeping the circumscribed area to a minimum.

To evaluate the head-loss performance of Sure-Flow strainers, several prototypes were fabricated and tested by PCI and the Boiling Water Reactor's Owners Group (BWROG) over a period of 9 months [Ref. 2]. One of the prototypes, which is generally referred to as Stacked-Disk #1 in the BWROG Utility Resolution Guidance (URG) [Ref. 3], was a 40%-scale prototype with six disks, five troughs between the six disks, a 13-in. core tube, a 30-in. outside diameter, and a 2.5-ft-long stacked-disk strainer. A larger prototype, which was referred to Stacked-Disk #2, was a 4-ft-long strainer with a core tube diameter of 26 in. and a stack outer diameter of 40 in. Both the BWROG and PCI tested the head-loss performance of these strainers. The testing procedure and the results of the testing are summarized in Refs. 3–6. An engineering correlation of the test data also was proposed by PCI but with several limitations.

The Sure-Flow strainer is not a "one-size fits all" type of standardized strainer. Instead, the concept promoted by PCI is to use similarly designed strainer modules of various sizes and quantities as necessary for each plant. The overall approach is that the individual plant first would determine the anticipated debris loading and the strainer design criteria applicable to that plant. PCI and its associated contractors would determine the size and number of stacked-disk modules necessary to meet the design criteria. For this approach to be successful, the PCI team of contractors needed a model that accurately predicts the head-loss performance of a generic PCI Sure-Flow strainer. The ITS Corporation (ITS) adapted a generic head-loss model used in the NUREG/CR-6224 study [Ref. 7] and extended it to the stacked-disk strainer geometry [Ref. 8]. ITS developed a proprietary computer code named HLOSS to automate the head-loss calculations performed for each plant. The overall technical approach for using the NUREG/CR-6224 correlation to predict PCI Sure-Flow strainer performance was validated by comparing the correlation predictions with the head-loss data listed in Refs. 2–4.

1.2 Objectives of the LANL Technical Review

The PCI test data and the ITS head-loss model were used by many licensees. Because of this, NRC tasked LANL to perform an in-depth review of the PCI head-loss data and examine the validity of the ITS head-loss model(s). This report summarizes LANL's findings.

1.3 References

1. Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA Generated Debris, G. Zigler, et al., Science and Engineering Associates, Inc., Prepared for Nuclear Regulatory Commission, NUREG/CR-6224, September 1995.

2. The Development and Testing of Performance Contracting, Inc., Sure-Flow Stacked Disk Suction Strainer for BWR ECCS Lines, G. H. Hart, Performance Contracting, Inc., February 1996.

3. Utility Resolution Guidance for ECCS Strainer Blockage, General Electric Nuclear Energy Company, Report No. NEDO-32686, Rev. 0, Class 1, November 1996.

4. Summary Report on Performance of Performance Contracting, Inc., Sure-Flow Suction Strainer with Various Mixes of Simulated Post-LOCA Debris, Revision 1., R. A. Biasca, Performance Contracting, Inc., September 1997.

5. Tests Conducted at the Fairbanks Morse Pump Company to Determine Head Loss Performance of PCI Bare Sure-Flow Strainer, Tech. Doc. No.: PCI-NPD-CE03, June 1997.

6. Results of ECCS Sure-Flow Strainer Testing for Performance Contracting, Inc., Rev. 0, A.E. Kaufman, Continuum Dynamics, Inc., Technical Note No. 96-22, December 1996.

7. A Generalized Correlation for Pressure Drop Across Fibrous Debris Beds, D. V. Rao, Calculational Note, Science and Engineering Associates, Inc., December 1996.

8. Comparison of Head Loss Model Based on NUREG/CR-6224 with PCI Full-Scale Strainer Test Data, P. Mast and F. Souto, Innovative Technology Solutions Corporation, Presented to US Nuclear Regulatory Commission, Rockville, Maryland, February 1997.

2.0 FINDINGS OF LANL REVIEW AND ANALYSES

2.1 PCI Strainer Testing Program

The head-loss testing data were obtained primarily for two prototypes, which are referred to here as the PCI-1 and PCI-2 strainers. Table 1 provides the geometrical details of these strainers.

Table 1. Geometrical Details of the PCI Prototype Strainers.

Parameter	PCI-1	PCI-2
Active Length (in.)	30	48
Core Diameter (in.)	13	26
Outer Diameter (in.)	30	40
Gap Width (in.)	2.125	2
Perforated Plate Area (ft^2)	64	169
Circumscribed Area (ft^2)	19.3	56
Interstitial Gap Volume (ft^3)	3.53	10.3

The head-loss data for these strainers were obtained for the following configurations.

- Clean Strainer (to estimate frictional losses resulting from the plate, core tube, etc.)
- Strainer with Nukon Fiber
- Strainer with Nukon Fiber and Sludge
- Strainer with Reflective Metal Insulation (RMI)

The head-loss data from these tests are given in Tables 2 and 3 except for the clean-strainer head-loss data. The PCI test program followed the test procedures and quality assurance (QA) plans described in the BWROG URG [Ref. 3].

2.1.1 Clean-Strainer Head Loss

The clean-strainer head-loss data were obtained at two different facilities: (1) the Electric Power Research Institute (EPR)I facility used in the BWROG testing [Ref. 3] and (2) Fairbanks Morse Pump Company [Ref. 5]. These data are plotted in Fig. 1 along with the clean-strainer head-loss data for other strainer models examined by the BWROG (e.g., the 60-point strainer and the truncated cone). As evident from Fig. 1, the truncated cone and the advanced designs resulted in about the same clean-strainer head loss.

Table 2. Strainer Head-Loss Data for PCI Sure-Flow.

Str/ Run	Flow Rate (gal./ min)	T (F)	Fiber Mass (lbm)	CP (lbm)	RMI (ft^2)	Head Loss (in. H_2O)
PCI-2	5000	59	17	85	0	19
95-2	2500	59	17	85	0	7
	3750	59	17	85	0	12
	4625	59	17	85	0	16
	7500	59	17	85	0	24
	9250	59	17	85	0	24
	10000	59	17	85	0	28
PCI-2	5000	58	25	100	0	25
95-3	2500	58	25	100	0	12
	3750	58	25	100	0	18
	4625	58	25	100	0	23
	7500	58	25	100	0	29
	9250	58	25	100	0	31
	10000	58	25	100	0	32
	5000	58	25	100	0	15
PCI-2	5000	58	3	100	0	10
95-4	2500	58	3	100	0	10
	3750	58	3	100	0	10
	4625	58	3	100	0	10
	7500	58	3	100	0	20
	9250	58	3	100	0	20
	10000	58	3	100	0	20
	5000	58	3	100	0	10
PCI-2	5000	60	50	100	0	66
95-5	2500	60	50	100	0	28
	3750	60	50	100	0	46
	4625	60	50	100	0	62

Table 2 (cont). Strainer Head-Loss Data for PCI Sure-Flow.

Str/ Run	Flow Rate (gal./ min)	T (F)	Fiber Mass (lbm)	CP (lbm)	RMI (ft^2)	Head Loss (in. H_2O)
PCI-2	2500	69	25	100	800	12
96-2	3750	69	25	100	800	19
	5000	69	25	100	800	28
	7500	69	25	100	800	35
	10000	69	25	100	800	52
PCI-2	5000	69	100	0	0	73
96-3	2500	70	150	0	0	56
	3750	70	150	0	0	91
	5000	70	150	0	0	120
	2500	71	200	0	0	74
	3750	71	200	0	0	127
	5000	71	200	0	0	166
	2500	72	250	0	0	100
	3750	72	250	0	0	164
	5000	72	250	0	0	213
	2500	73	300	0	0	116
	3750	73	300	0	0	194
	4000	73	300	0	0	199
PCI-2	2500	69	100	100	0	65
96-4	3750	69	100	100	0	104
	5000	69	100	100	0	147
	6250	69	100	100	0	177
PCI-2	2500	70	200	100	0	129
96-5	3000	70	200	100	0	156
	3500	70	200	100	0	200
	3750	70	200	100	0	230

	7500	60	50	100	0	98
	10000	60	50	100	0	122

This table does not include the head-loss data obtained for PCI-1 design.

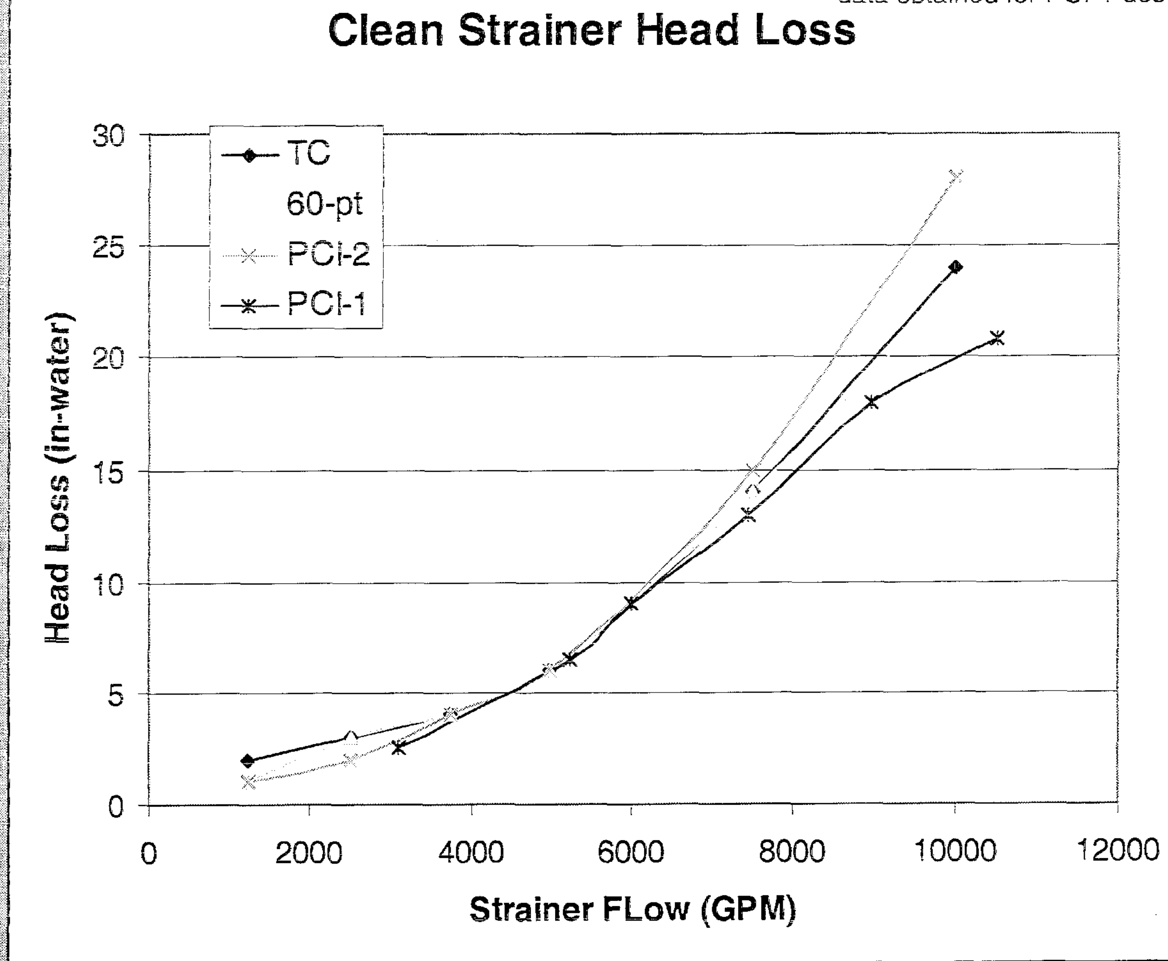

Fig. 1. Clean-Strainer Head-Loss for Various BWROG Strainer Designs [Ref. 3].

Table 3. Loaded-Strainer Head-Loss Data for PCI-1 Prototype Strainer [Ref. 3].

Str/ Run	Flow Rate (gal./min)	T (F)	Fiber Mass (lbm)	CP (lbm)	RMI (ft^2)	Head Loss (in. H_2O)
PCI-1	3750	64	6	0	0	26
#20	2500	64	6	0	0	14
	1250	64	6	0	0	5
PCI-1	2500	65	1	180	0	23
#21	1250	65	1	180	0	7
PCI-1	2500	69	3	180	0	65
#22	1250	69	3	180	0	25
	2500	69	3	240	0	72
	1250	69	3	240	0	22
	3750	69	4	240	0	250
	2500	69	4	240	0	195
	1250	69	4	240	0	100
	2500	69	6	240	0	350

The clean-strainer head loss plotted in Fig. 1 includes the acceleration head-loss component, and the connecting flange head loss. PCI developed an empirical correlation for the strainer head loss by itself as follows.

$$\Delta H_{cs} = A + K_1 \nu V_{en} + K_2 (V_{en}^2/2g) ,$$

where

ΔH_{cs} = clean-strainer head loss (ft-water),
A = 0.0022,
K_1 = 1024,
K_2 = 0.8792,
ν = kinematic viscosity (ft^2/s),
V_{en} = entrance water velocity (ft/s), and
g = the gravitational constant (32.2 ft/s^2).

This correlation appears to perform well and, in fact, is comparable in head-loss prediction to the head-loss values used in the Dresden strainer head-loss analyses.

2.1.2 Strainer Head-Loss Data for Simulated Fibrous Debris

Tables 2 and 3 summarize the head-loss data obtained for the PCI prototype strainers [Refs. 3, 4, and 6]. The following observations were made during the testing.

- With the exception of Test ID 95-4, the filtration efficiency measured for most of the tests varied between 75% and 97% with one exception. In the case when the total debris loading for PCI-2 is 3 lb (or 1.2 ft^3) dispersed on a strainer surface area of approximately 170 ft^2 the measured capture efficiency was 40%. For other debris loads where the bed thickness varied between 0.25 in. and several inches, the

measured filtration coefficient was much higher (75% to 97%). Of course, the higher efficiencies are also a reflection of the fact that the head-loss system is a closed-circuit system (in that the sludge is recycled several times).

- In selected experiments, PCI measured the actual volume of the debris and compared it with a theoretical debris volume to draw conclusions regarding debris bed compressibility. Based on this, it was determined that the NUREG/CR-6224-suggested compression equation performs fairly well for the Nukon debris in conjunction with the stacked-disk strainers.

PCI developed a purely empirical equation to predict the head-loss performance of the PCI strainer loaded with the fibrous debris and particulate debris. This equation is given as

$$\Delta H_{Nukon} = A + B\,(Q/A_s) + C\,(M_f/A_s) + D\,(Q/A_s)(M_f/A_s)\ .$$

This is a pure regression fit. The coefficients from the regression fit are as follows: A= 0.7696, B=-0.02292, C = -0.5406, and D = 0.08916. PCI noted that the validity of the regression fit could not be assured because the fit does not relate head loss to fundamental strainer properties such as strainer area vis-a-vis debris volume.

2.1.3 Strainer Head-Loss Data for Simulated Fibrous and RMI debris

The PCI strainer underwent a series of tests to capture the effect, if any, of adding RMI to the fibrous debris. Test 95-03 used 25 lb of Nukon and 100 lb of corrosion products on the PCI-2 prototype strainer. Test 96-02 is a repeat of Test 95-03 with the exception that approximately 800 ft^2 of RMI debris was added in addition to the Nukon and corrosion products. Table 4 presents the results for these tests. As evident from this table, addition of RMI does increase head loss at higher water velocities. The difference in measured head losses is 6 in. and 12 in., respectively, corresponding to flow rates of 7500 and 10,000 gal./min. This clearly establishes that the head-loss contribution of RMI should be carefully accounted for in the $NPSH_{Margin}$ estimates.

Table 4. Head-Loss Data from Tests 95-03 and 96-02.

Str/ Run	Flow Rate (gal./min)	T (F)	Fiber Mass (lbm)	CP (lbm)	ΔH (in. H_2O) o ft^2 of RMI Test 95-03	ΔH (in. H_2O) 800 ft^2 of RMI Test 96-02
PCI-2	5000	58	25	100	25	28
	2500	58	25	100	12	12
	3750	58	25	100	18	19
	4625	58	25	100	23	N/A
	7500	58	25	100	29	35
	9250	58	25	100	31	N/A
	10000	58	25	100	32	53

2.2 Analysis of Head-Loss Data

2.2.1 Background

The purpose of this section is to explore how the NUREG/CR-6224 correlation can be adapted for PCI stacked-disk strainers. The NUREG/CR-6224 head-loss correlation was developed based on experimental data obtained for flat-plate and truncated-cone strainers. In its original form, it should be used only for these type of strainers. However, it can be easily modified or adapted to predict head loss across more complex strainer shapes, such as General Electric and PCI stacked-disk strainers. This adaptation was sought by the staff for several reasons. First, such an adaptation would provide an independent tool that can be used by the staff to evaluate the performance of strainers installed at various operating BWR plants. Such a tool can be very effective at evaluating licensee analyses during brief on-site plant reviews. Second, because the basic correlation was validated previously over a wide range of operating parameters (debris loads, sludge-to-fiber ratios), the adapted correlation can be used by the staff to predict a strainer performance for a parameter range beyond which that strainer was originally tested. Finally, this exercise also will provide the assurance that the ITS-proposed method of correlating PCI strainer head-loss data is adequate.

Phenomenological Understanding of Debris Deposition on Stacked-Disk Strainers

The basic idea of stacked-disk strainers is to maximize the perforated plate area for a given projected size of the strainer (also known as the circumscribed size). The head loss caused by these strainers is significantly controlled by such factors as (a) the gap volume, (b) the plate surface area, and (c) the change in deposition area with debris loading. The importance of these factors can be explained by considering the schematic presented in Fig. 2. This schematic shows the debris build-up on a PCI stacked-disk strainer.

Initially, the debris would accumulate nearly uniformly on the strainer plate surface. At this extreme, the strainer surface area available for deposition would be very close to the total perforated plate area. Thus, head loss should be able to be predicted by treating the plate as a flat plate with a flow area equal to the total plate area. The flow velocity and bed thickness then would be as follows.

$$V_{thin\text{-}bed} = Q\ (ft^3/sec)/A_{plate}$$
$$t_{thin\text{-}bed} = M_{fiber}/(\rho_f \cdot A_{plate})$$

The resulting head loss can be calculated using the NUREG/CR-6224 correlation or similar correlations.

On the other extreme, when the loads are very high, the gap volume first would be filled completely, and the remaining debris would be deposited on the circumscribed area of the strainer. For this portion of the debris buildup, once again, the NUREG/CR-6224 correlation can be used with the velocity and thickness evaluated using circumscribed area instead of plate area. For moderate loads, some sort of interpolation scheme that gradually decreases flow area can be sought.

One of the key parameters necessary to apply this criterion is the compressibility of fibrous debris beds. NRC measurements have shown that beds tend to be highly compressible when subjected to large head loss across them. NUREG/CR-6224 provided the following relationship that can be used to calculate actual bed density as a function of the pressure drop across the bed:

$$\rho_f = \rho_{fo}\, 1.3(\Delta H/\Delta L_o)^{0.38}\ .$$

The following section provides the head-loss equations used to perform these calculations.

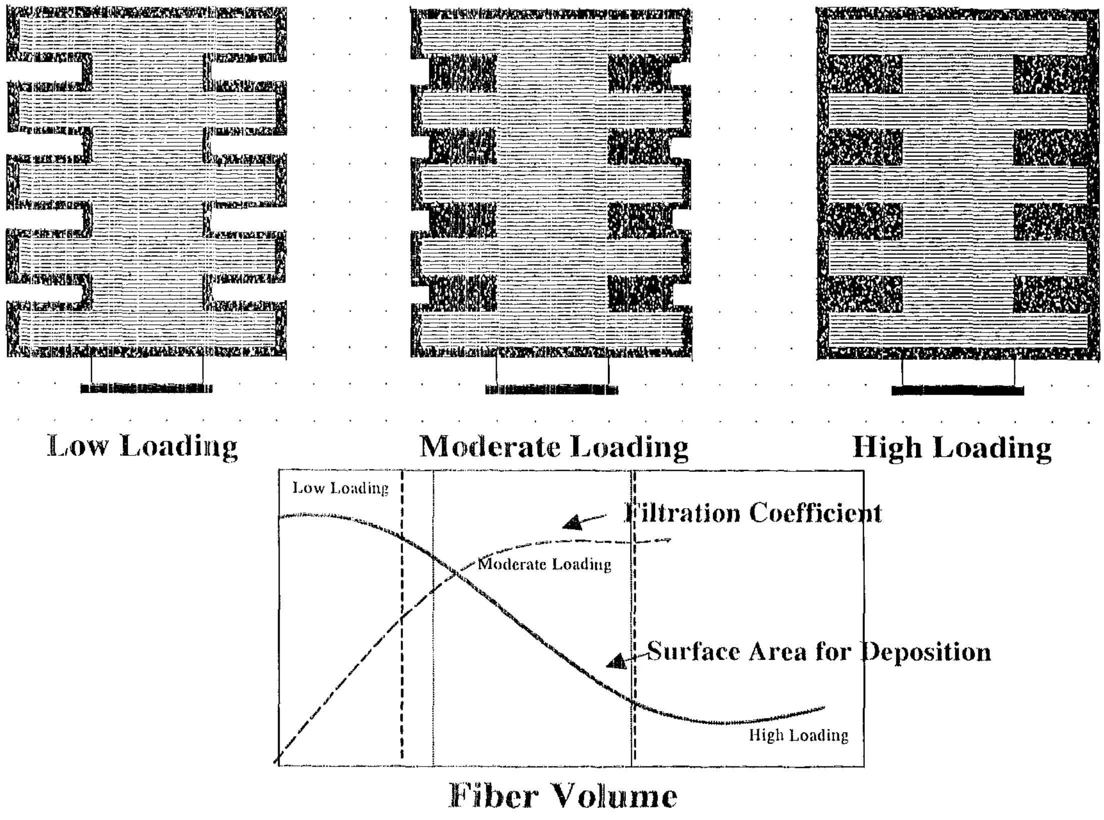

Fig. 2. Schematic Illustration of Debris Bed Buildup on Stacked-Disk Strainers.

2.2.2 Application of Modified NUREG/CR-6224 Correlation to PCI Strainers

The following methodology was used to calculate head loss across the debris bed for different debris bed thicknesses. The general head loss equation used is

$$\Delta H = 3.5 \cdot S_v^2 \cdot (1-\varepsilon_m)^{1.5}\left[1+57(1-\varepsilon_m)^3\right]\mu V \cdot \Delta L \quad .$$

All the symbols are described in Appendix B to NUREG/CR-6224. Units are in FPS; however, ΔH is in ft-water and ΔL is in inches.

Thin-Bed Approximation ($V_f/V_{gap} < 0.30$)

For thin beds, the whole plate surface area provides a location for debris deposition. In this case,

ΔL_o(in)	$= (12 \,.\, M_{fiber})/(\rho_{fo} \,.\, A_{plate})$,
ΔL	$= \Delta L_o \,(\rho_f/\rho_{fo})$,
V (ft/s)	$= V_{plate} \equiv Q(ft^3/s)/A_{plate}$, and
ρ_f/ρ_{fo}	$= 1.3(\Delta H/\Delta L_o)^{0.38}$.

Intermediate Bed Approximation ($1.0 > V_f/V_{gap} > 0.30$)

For intermediate loadings, the area available for deposition gradually decreases and the velocity within the bed gradually increases. An approximate formula for evaluating head loss is

ΔL_o(in)	$= (12 \,.\, M_{fiber})/(\rho_{fo} \,.\, A_{plate})$,
ΔL	$= \Delta L_o \,(\rho_f/\rho_{fo})$,
V (ft/s)	$= V_{plate}\,(1-(V_f/V_{gap} - 0.3)) + V_{cir}\,(V_f/V_{gap} - 0.3)$,
V_{plate}	$\equiv Q(ft^3/s)/A_{plate}$,
V_{circ}	$\equiv Q(ft^3/s)/A_{circ}$, and
ρ_f/ρ_{fo}	$= 1.3(\Delta H/\Delta L_o)^{0.38.}$

This relation simply provides a means for calculating head loss using a volume-averaged velocity through the bed.

Thick-Bed Approximation ($V_f/V_{gap} > 1.0$)

Head loss from a thick bed is a sum of head loss resulting from the fully loaded strainer and a calculated contribution from the circumscribed portion using the following closure relationships.

ΔL_o(in)	$= (12 \,.\, M_{fiber})/(\rho_{fo} \,.\, A_{circ})$
ΔL	$= \Delta L_o \,(\rho_f/\rho_{fo})$
V (ft/s)	$= V_{circ} \equiv Q(ft^3/s)/A_{circ}$
ρ_f/ρ_{fo}	$= 1.3(\Delta H/\Delta L_o)^{0.38}$

Although these equations appear complex, they can be solved easily. The results of the comparison are presented in Figs. 3 and 4. As shown in these figures, the NUREG/CR-6224 correlation can predict the head-loss data for PCI strainers fairly accurately (within ±25%)..

Figure 3 presents a point-by-point comparison of NUREG/CR-6224 model predictions with the experimental data. All the points were within ±25% bounds, indicating good agreement between the correlation and the test data. This agreement confirms that the head loss caused by deposition of debris on stacked-disk strainers can be simulated adequately by accurately accounting for the change in the flow cross section. This comparison also suggests that the PCI approach is probably accurate, although we cannot make such a positive conclusion until we examine how the approach was implemented in the HLOSS computer code.

Figure 4 presents a plot of effective strainer area as a function of the volume of debris being deposited. This curve can be used to input the strainer area into the BLOCKAGE computer code.

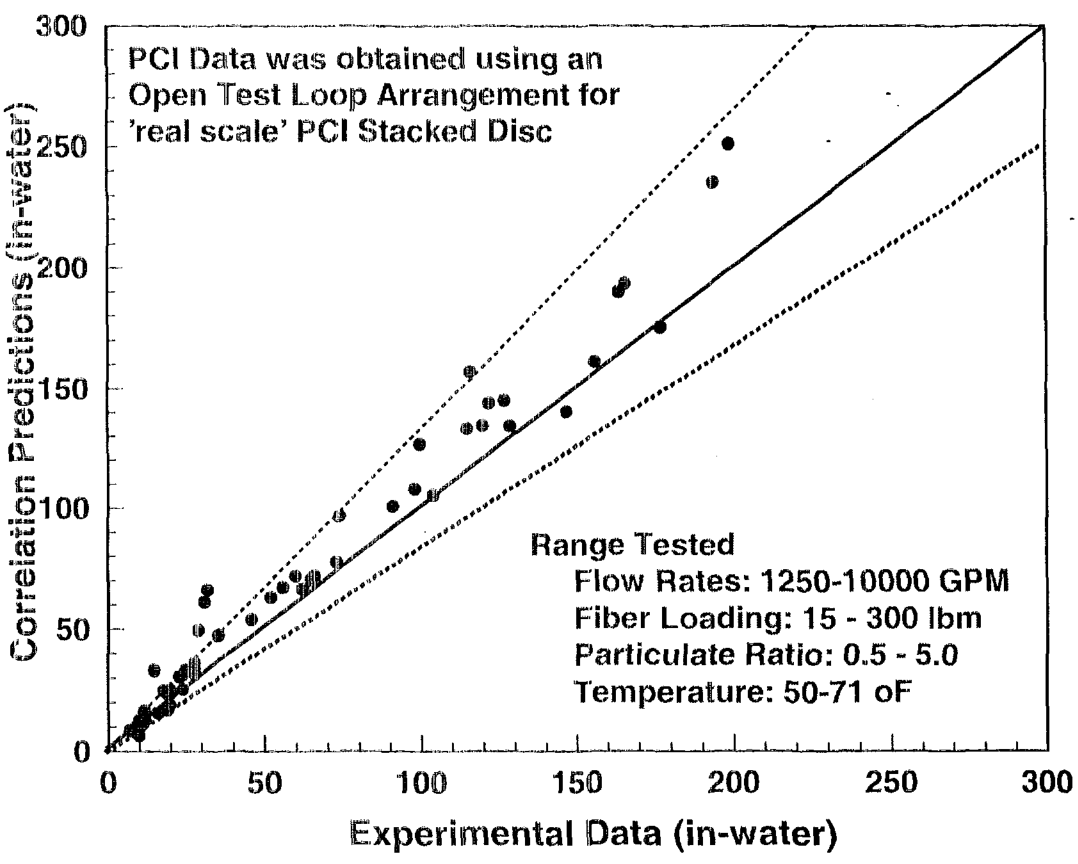

Fig. 3. Point-By-Point Comparison of Model Predictions with Test Data.

Conclusions

The review concluded that PCI was acceptable methods for obtaining head loss data. However, the data cannot be directly used in the plant specific analyses because the strainer design is not "one size fits all." The correlation proposed by PCI is not valid for application because it is not based on fundamental parameters.

The review also demonstrated that NUREG/CR-6224 is an effective method for predicting PCI strainer performance. Hence this correlation can be used in the NRC review of individual licensee submittals.

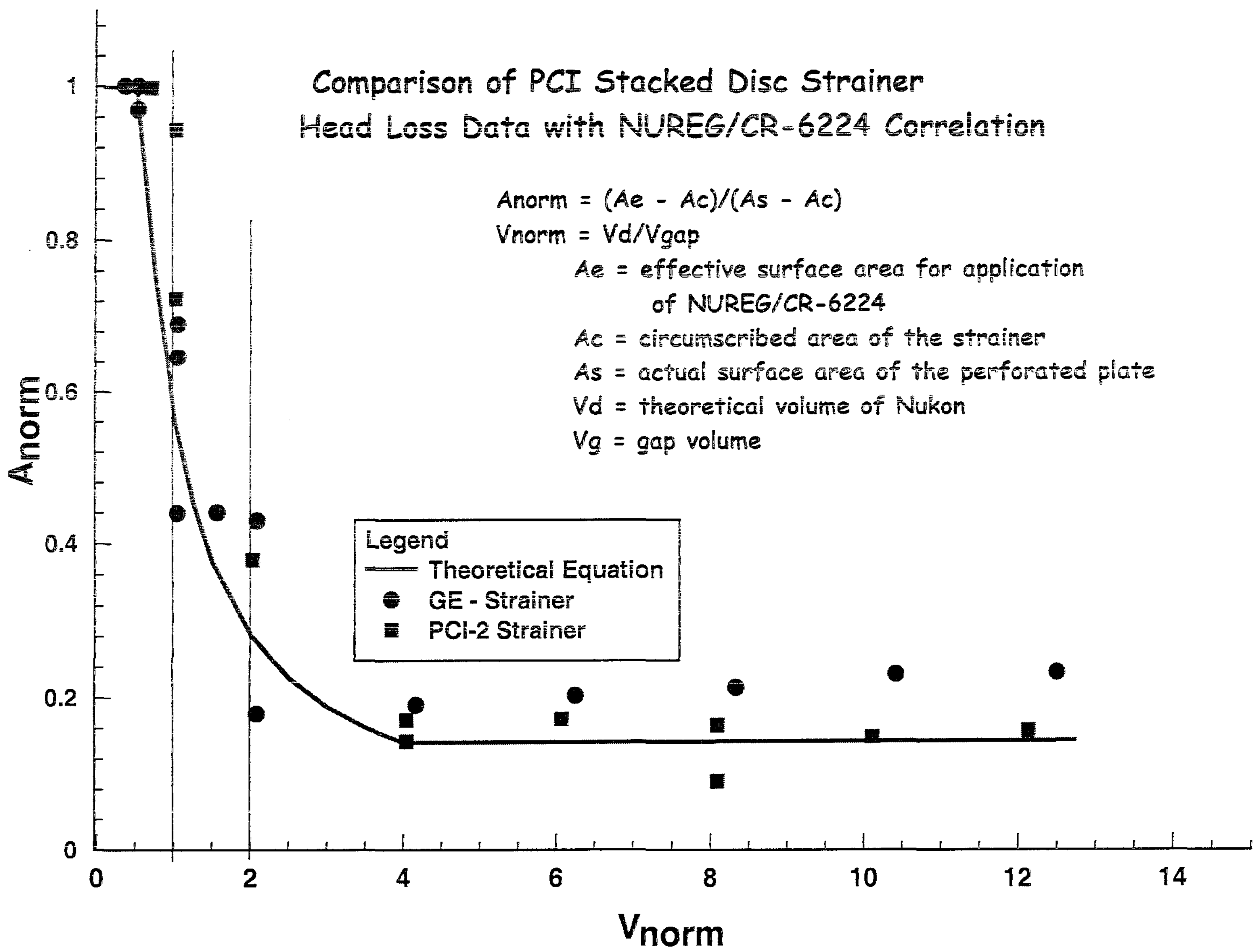

Fig. 4. Change in Effective Strainer Surface Area as a function of the Volume of Debris Deposited.