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STANDARDIZED PRESSURE FIELD EXTENSION CALCULATIONS

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ABSTRACT

Radon mitigators and researchers measure the pressure field extension (PFE) beneath a slab in order to determine whether an active subslab depressurization (ASD) system is applicable, or to the case of existing ASD system, to evaluate its performance. PFE is measured by drilling one or more small holes through the slab and measuring the differential pressure across the slab while a fan or vacuum depressurizes the subslab volume through a larger hole located at some distance from the test hole(s). Unfortunately PFE measurements have not been standardized, so it is generally difficult for mitigators or researchers to compare PFE measurements from different sites. This paper suggests a standardized technique for making and evaluating PFE measurements, applies it to several PFE data sets, and evaluates the range of probable PFE measurements.

INTRODUCTION

ASD is generally thought to work by depressurizing the subslab volume and preventing the entry of radon-containing soil gas into the occupied space. Since this depressurization effect generally decreases as the distance from the stack increases, it would be helpful to have a parameter to characterize this PFE decrease with increasing distance from the ASD stack. There are several variables, such as slab airtightness and subslab aggregate size, that influence PFE, and some researchers have developed theories that propose to account for the physics of PFE (Gadsby, 1991). However, instead of theoretical models of PFE, this paper is based on the simple empirical observation that PFE measurements tend to show a constant percentage drop in subslab pressure as the distance between the PFE test hole and the ASD hole increases.

For example, if the pressure in the ASD hole is -1.0 inches of water column (" wc), and a PFE test hole 10 ft away shows a pressure of -0.1" wc (a drop of 90% from the ASD hole), then a second test hole 20 ft away from the ASD hole might show a pressure of 0.01" wc (a drop of 99% from the ASD hole and a drop of 90% from the first PFE test hole). Therefore, if PFE measurements were standardized to a fixed distance (e.g. 10 ft) then new PFE measurements could be compared to our example which showed a PFE % Drop of 90% in 10 ft. This paper proposes that all PFE measurements be adjusted to a standardized percent drop in pressure over a 10 ft (3 meter) distance. The remainder of this paper will describe the PFE calculations and show some experimental data sets.

Table 1 shows the range of PFE % Drop values that the author has measured, along with indications of the subslab conditions that may have accounted for them. This table is based on a handful of measurements and it is presented, not as a comprehensive analysis, but to suggest that a large database of PFE measurements should be collected in order to more thoroughly understand the relation between PFE and subslab conditions.

Table 1 - Expected PFE Range of Values

PFE % Drop @10 ft	PFE measured 10' from an ASD hole with -1.0' wc suction	Expected Subslab Conditions
0% to 25%	-1.0" wc to -0.75" wc	very good aggregate and sealing
25% to 90%	-0.75" wc to -0.10" wc	some aggregate under slab
90% to 99%	-0.10" wc to -0.01" wc	poor aggregate and/or leaky subslab
99% to 99.9%	-0.01" wc to -0.001" wc	sand

PFE % DROP CALCULATION

The pressure field around an ASD stack is generally observed to decrease as the radial distance of the test hole increases, and this decrease appears to be exponential. The primary evidence for PFE data following an exponential function is the observation that a plot of subslab pressure versus distance data generally lies along a straight line on a semi-log plot. This paper show some confirming data, and will assume an exponential pressure

$$p(x) = p(y)\,\alpha^{\frac{x-y}{\beta}} \quad (1)$$

versus distance relation as shown in Equation 1:
Where $p(y)$ = pressure in PFE test hole at radial distance y from the ASD hole,
$p(x)$ = pressure at PFE test hole at radial distance x the ASD hole,
α = fraction of the pressure remaining after distance b, and
β = reference distance (10 ft or 3 m).

If the PFE data fit this equation, then we can characterize each slab by a parameter that describes the percent drop per reference distance.

$$PFE\,\%\,Drop_{\beta} = 100(1-\alpha) \quad (2)$$

For example, suppose that PFE data are fit to Equation 1, with the parameters α = 0.8 and β = 10 ft. Then Equation 2 gives

$$PFE\,\%\,Drop_{10ft} = 100(1-0.8) = 20\,\% \quad (3)$$

If the PFE data is analyzed this way, then it provides a simple way of characterizing data from various slabs. One limitation of this analysis is that pressure data near the stack (within a few ft) often does not fit this equation well, perhaps because the flow pattern is altered by the inhomogeneities in the subslab materials near the stack. This suggests that whenever possible, the initial PFE measurement be made about 3 ft (1 meter) away from the ASD pit or the vacuum hole. Of course in many cases this may not be possible, e.g., when analyzing old PFE data sets. Equation 4 shows how to calculate PFE % DROP directly from PFE data. Using the example of the data in the first paragraph of this section, Equation 5 provides a sample calculation:

$$PFE\,\%\,DROP = 100(1-(\frac{p(x)}{p(y)})^{\frac{\beta}{x-y}}) \tag{4}$$

$$PFE\,\%\,DROP = 100(1-(\frac{0.01}{0.1})^{\frac{10.0}{20.0-10.0}}) = 90\% \tag{5}$$

Factors that Affect PFE

PFE appears to depend on a combination of factors including: 1) aggregate air flow resistance or porosity, 2) sealing of the subslab volume, and 3) airflow resistance in the area around the stack pipe. Laboratory and theoretical studies of PFE have been performed (Craig, 1991), but it is difficult to separate the effect of the factors in the limited field data that are available. Some general observations can be made on the three factors:

1. SUBSLAB VOLUME SEALING - If the subslab volume is perfectly sealed (by the slab above and soil one each side and below), then the PFE % Drop will be zero because the volume will be uniformly depressurized. However, if a crack is opened at the edge, then it is assumed that a non-zero PFE % Drop would be measured that is a function of the size of the crack and the porosity of the aggregate. Note that if the soil beneath the foundation is porous and does not provide a tight air seal, then neither porous aggregate nor a well-sealed slab will produce low values of PFE % Drop. For example, in areas where the soil is relatively impermeable (e.g., high clay content), low values of PFE % Drop should be possible, but areas with porous soils (e. g., glacial tills) may expect higher values of PFE % Drop.

2. AGGREGATE POROSITY - If the aggregate is resistant to air flow, then higher values of PFE % Drop can be expected. Sand has been reported to cause very high PFE % Drop (e.g., 99.9% per 10 ft), while large diameter clean gravel may cause PFE % Drop as low as a few percent per 10 ft.

3. FLOW NEAR STACK PIPE - Since the air flow through the aggregate bed is highest where the flow enters the stack pipe, the magnitude of the pressure field can often be increased by lowering this resistance by either increasing the size of the suction pit in the aggregate around/below the stack pipe, or by using perforated pipe extending out from the stack pipe to distribute the flow through the aggregate bed. Although these measures have been observed to increase the pressure at all points across the slab, pressure measurements suggest that the PFE % Drop in far field regions beyond the pit or perforated pipe are independent of the conditions near the stack.

Computer Program to Analyze PFE

A computer program PFE.COM was written to fit the PFE data to Equation 1. This program allows PFE data to be entered, edited, fit to the equation, and plotted the computer screen. PFE data sets can be saved in disk data files, together with identifying information. Test data files from several PFE test locations are included. Copies of this program are available from the author.

PFE SAMPLE DATA

The Francis A. Desmares Elementary school near Flemington, NJ was completed in September 1991, and it was selected for EPA study because the 1989 building design included a rough-in of an ASD system with 10 stacks and a network of perforated pipes in the subslab aggregate (Saum, 1993). Subslab pressure field measurements after construction indicate that one or two stacks equipped with exhaust fans would probably provide adequate radon mitigation performance, and that one active stack can depressurize at least 50,000 sq ft if subslab barriers are absent, and the soil beneath the aggregate layer is impermeable. The Desmares subslab depressurization was achieved without significant additional slab sealing.

On August 14 and 15, 1991, the site was visited to collect subslab measurements just before the floor covering was laid down. Since the site was being readied for occupancy in early September, this was the last chance for extensive slab drilling. A temporary exhaust fan system was installed on one of the stacks and PFE measurements were made through the drilled 1/4 in. subslab test holes. Fig. 1 shows the distance to the test holes from the two stacks (#5 and #7) that were depressurized. Measurements were also made of stack pressure, stack flow, subslab radon, and stack exhaust radon concentration.

PFE was measured when a 150 Watt radon exhaust fan was operating on Stack 7 with all the other stack sealed, and Fig. 2 graphs this PFE data against a best curve fit to Equation 1. Note that data points from test holes F, G, H, M and N are across a footing from the stack and they are not used in the curve fit. Test hole O showed no pressure during any of the stack tests and it appears that the Northeast section of the slab is effectively isolated by the gymnasium subslab wall footings. The combination of two subslab wall barriers and the long distance (158 ft) may be reason for the lack of PFE at test hole O, or it is possible that the aggregate that was reportedly placed under the footings because of waterlogged soil was not placed uniformly near point O. Test hole L showed no pressure during this test, but it was depressurized in subsequent stack tests. Note that the two Western pods are slightly depressurized although they are separated for the stack by a narrow section of slab, a footing and an expansion joint!

Hole E had a -155% error (lower than expected pressure). This test hole was drilled in a saw cut control joint, and the pressure may be low because there is nearby air leakage through the crack. The PFE % Drop parameter indicates a 16.3% drop in pressure every 10 ft for this set of data. For instance, Equation 1 predicts that 50 ft away from the stack, the subslab pressure will drop by a factor of be $(1-.163)^5 = .411$, or 41.1% of the value near the stack. Note that the pressure at the top of the stack near the fan is rather high (1.70 " wc) which is much higher than a similar test (to be discussed) at a more centrally located stack. This high pressure suggests a higher flow resistance at this stack which is located near the edge of the slab. This stack may have more resistance than a centrally located stack because it has only two 40 ft sections of perforated pipe radiating out from it, while most of the other stacks have 4 perforated pipes, and the edge location may prevent it from drawing air from a full 360 degrees of aggregate.

Figs. 3 and 4 show data and calculations when the exhaust fan is moved to a more centrally located stack (#5) that has four 40 ft sections of perforated pipe radiating out from it under the slab. All stacks except 5 were sealed for these PFE measurements. Again the PFE test holes that are across subslab wall footings are not used in the curve fit because of the increased airflow resistance expected from these footings, even though there is reportedly gravel under them. Again the data for test hole E are very low (-200% error below the best fit to the other PFE data), as expected if there is a significant leakage near it. The flow in stack 5 is much higher than in stack 7 (260 versus 140 cfm), and the pressure is lower (0.90 versus 1.7 " wc), suggesting that there is less flow resistance in stack 5. The lower flow resistance may be due to the four perforated pipes extending out from stack 5 (rather than the 2 from stack 7) and the more central location of stack 5 which allows it to draw air flow from all 360 degrees around it.

The computed PFE % Drop for is 16.3% for maximum fan flow in stack 5, very close to the PFE % Drop of 16.1% computed for stack 7. This suggests that the PFE % Drop parameter is a good measure of the general subslab conditions and not just the condition in and around the particular stack under test. Note that there is still no pressure at test hole O, but there is depressurization again at test hole N in one of the Western pods and at point H. The other pod was not accessible for testing because of a locked door. Test hole L at the farthest Northern end of the building now shows some depressurization.

Fig. 4 shows the effect of reducing the fan power with a speed controller on the stack 5 fan until the upper stack pressure drops from 0.90" wc (full power) to 0.25" wc. This experiment was run to simulate how the PFE % Drop parameter changes with decreasing fan power, decreasing pipe size, decreasing suction pit size, or shorter runs of subslab perforated pipe. If PFE % Drop is a measure of the subslab conditions, it would be expected that there would be little change in the parameter if the fan power is reduced. This hypothesis is confirmed by the calculation of PFE % Drop at 17.0%, very similar to the values of 16.1 and 16.3% from the previous figures and tables.

Desmares PFE Comparison With Another Building

Fig. 5 shows PFE calculations taken from data in (Craig, 1991). The building is a hospital in Johnson City, TN with a 56,000 sq ft slab that was built with radon control features. A single 6 in. stack is located in the middle of the slab and there are no interior footings. The ASD system differs from the Desmares school in that the slab sealing was attempted, a suction pit was used instead of perforated pipe, and an aggregate with a more uniform size was used (ASTM #5 aggregate specification). The sealing measures included a turned-down slab which eliminated the floor-to-wall crack, and the sealing of all control joints.

The figure and table show that the PFE % Drop for the Johnson City slab is 1.3% per 10 ft, less than 1/10 of the value measured at Desmares (about 17%). The PFE measurements at Desmares suggest that although the PFE is generally increased or decreased in magnitude by factors such as fan power, the flow resistance near the stack, and the stack placement, but the PFE % Drop is a property of the aggregate bed. This suggests that subslab suction pit is not the primary reason for the excellent performance of the Johnson City ASD system. The two remaining possibilities are the differences in the subslab aggregate layers and the slab sealing.

Both buildings have a minimum 4 in. depth of aggregate, but Desmares has ASTM #57 crushed aggregate while Johnson City has ASTM #5, a narrower size grading which does not include the smaller particles. The smaller particles can clog airflow pathways between the larger aggregate pieces. The Johnson City aggregate should have a lower airflow resistance, and therefore a lower PFE % Drop.

The slab sealing at Johnson City may be better than the sealing at Desmares because sealing was specified by the architect at Johnson City but not at Desmares. Note that the Johnson City PFE % Drop approaches the case that would be expected for perfect sealing --- uniform pressure field across the entire subslab volume, independent of the aggregate layer. However, no flow or pressure measurements were made before and after the Johnson City sealing that can be used to judge its effectiveness. At least two 8 in. by 16 in. holes in the slab for bathtub installation were not sealed. There was one indication that the sealing at Johnson City was not completely effective -- the stack flow at Johnson city was 200 cfm, which is similar to the maximum stack flow at Desmares (260 cfm) with similar fans (about 150 Watts).

The definitive explanation for the superior Johnson City PFE % Drop over the Desmares must wait for further experiments. But the Desmares data suggest that the differences between the subslab suction pit and the perforated pipe are not the major factor. It seems more likely that the aggregate or the slab sealing were more critical to obtaining good PFE % Drop, and the similar flow rates from the Johnson City and Desmares stacks suggest that the aggregate specification was the most important factor.

CONCLUSIONS

This paper presents a standardized way of measuring and calculating PFE so that measurements from different buildings and different researchers can be compared. A limited data set is analyzed that suggests that the PFE parameter is independent of flow and pressure, and that PFE is actually a measurement of subslab depressurization potential.

REFERENCES

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Saum, D.W., "Case Studies of Radon Reduction Research in Maryland, New Jersey, and Virginia Schools," EPA Office of Radiation and Indoor Air, 1993, EPA-600/R-93-211.

FIGURES

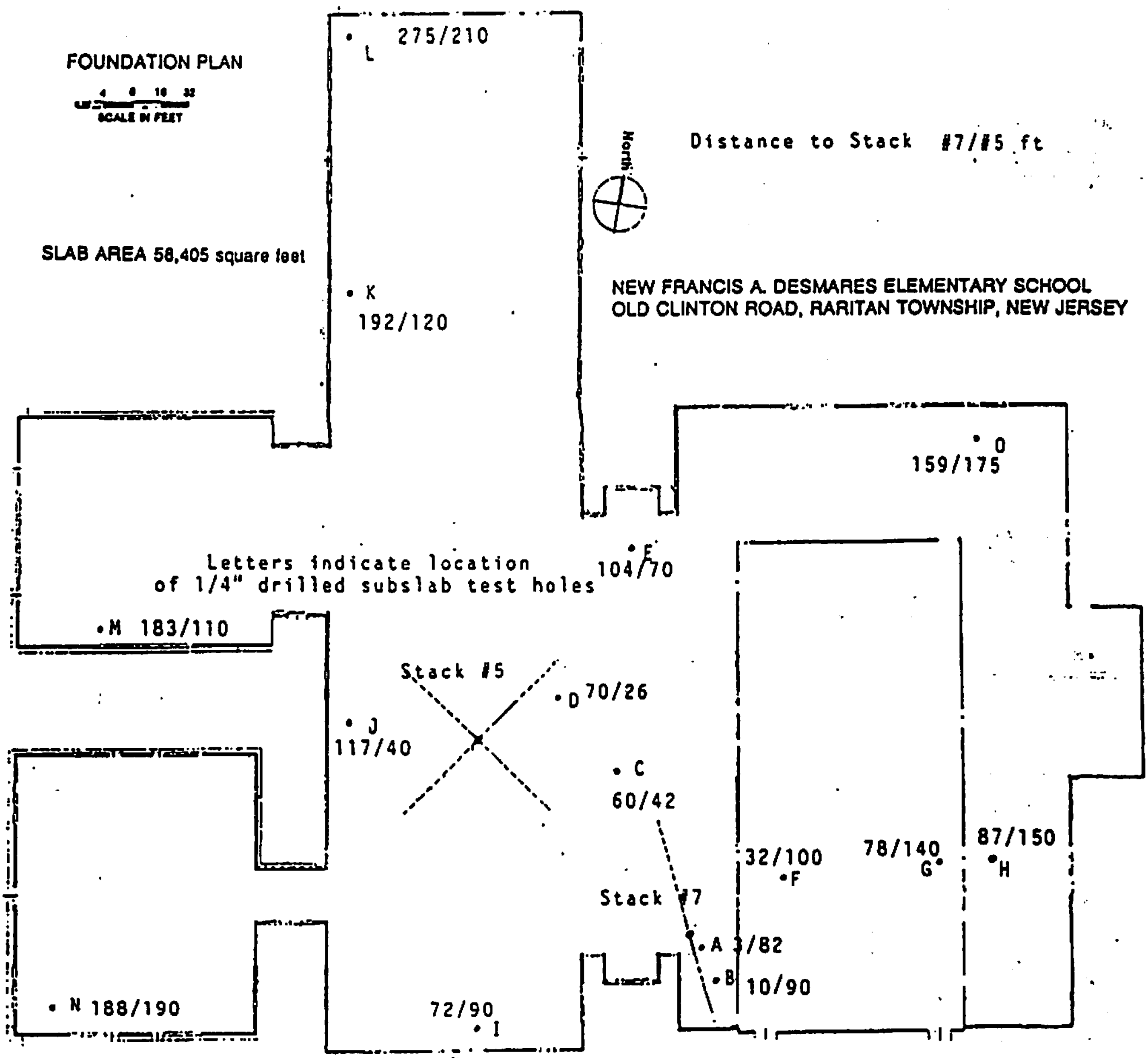

Figure 1 - Desmares Distance to PFE Test Hole Plan

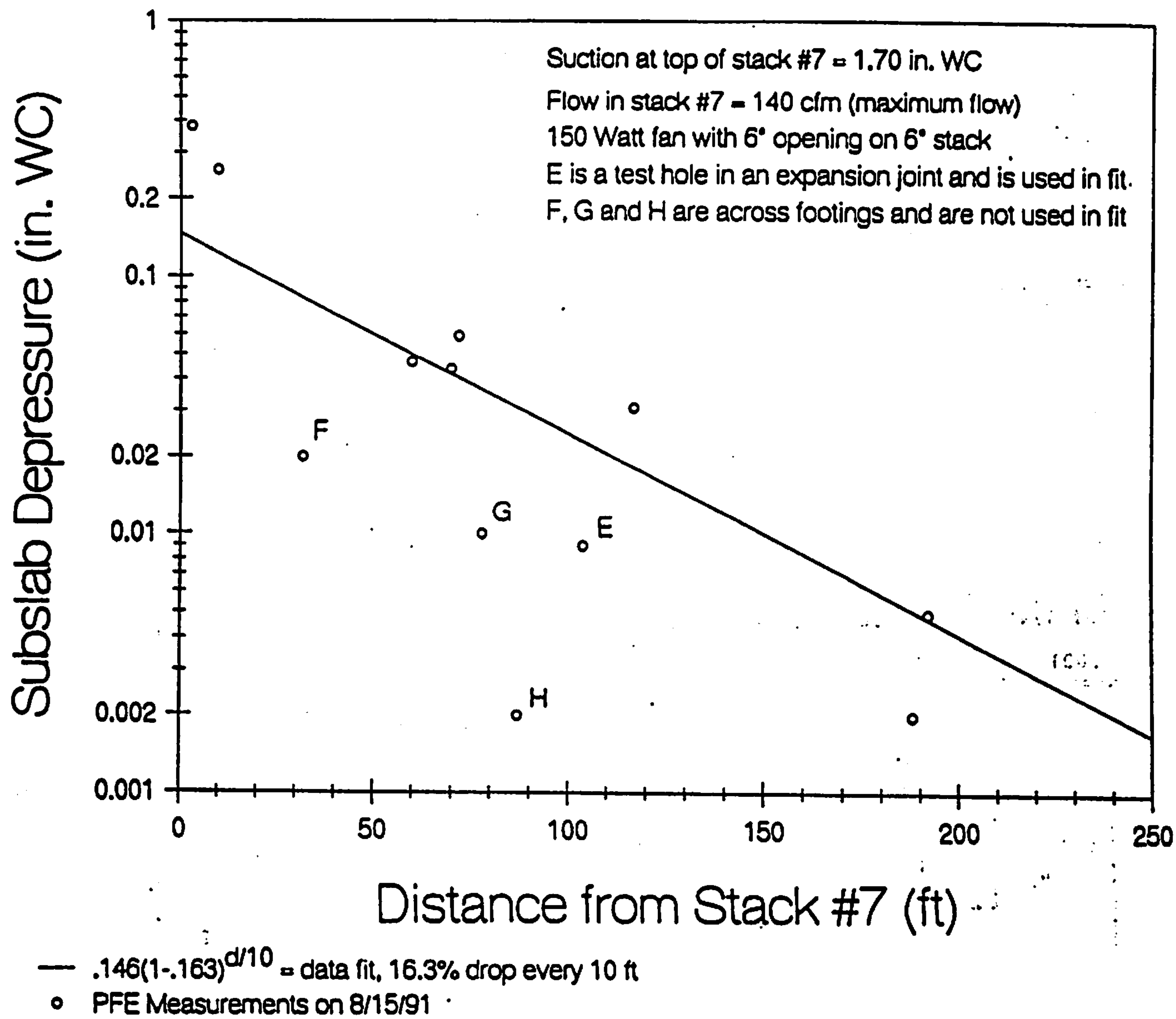

Figure 2 - Desmares Stack 7 PFE Plot

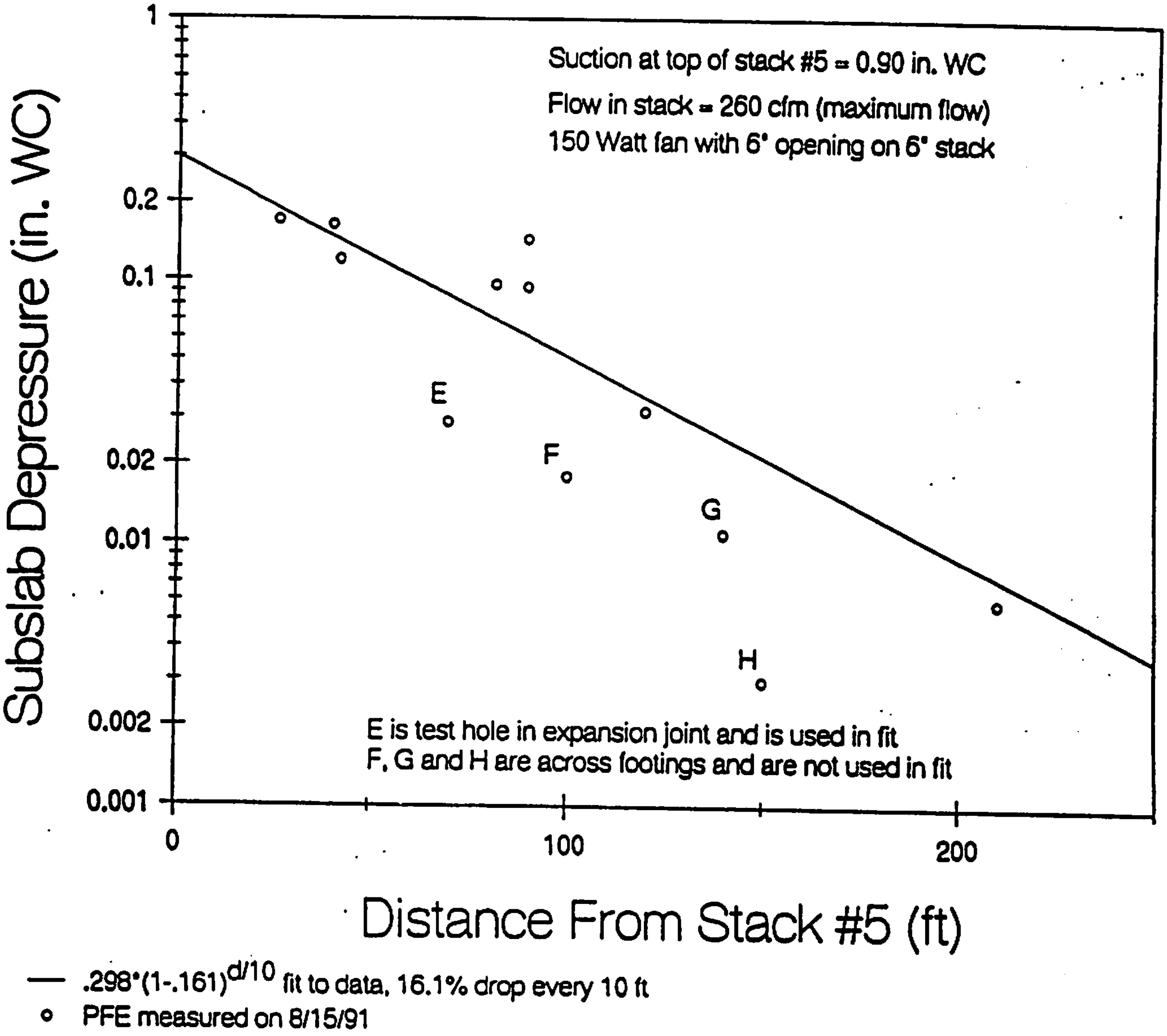

Figure 3 - Desmares Stack 5 High Flow PFE Plot

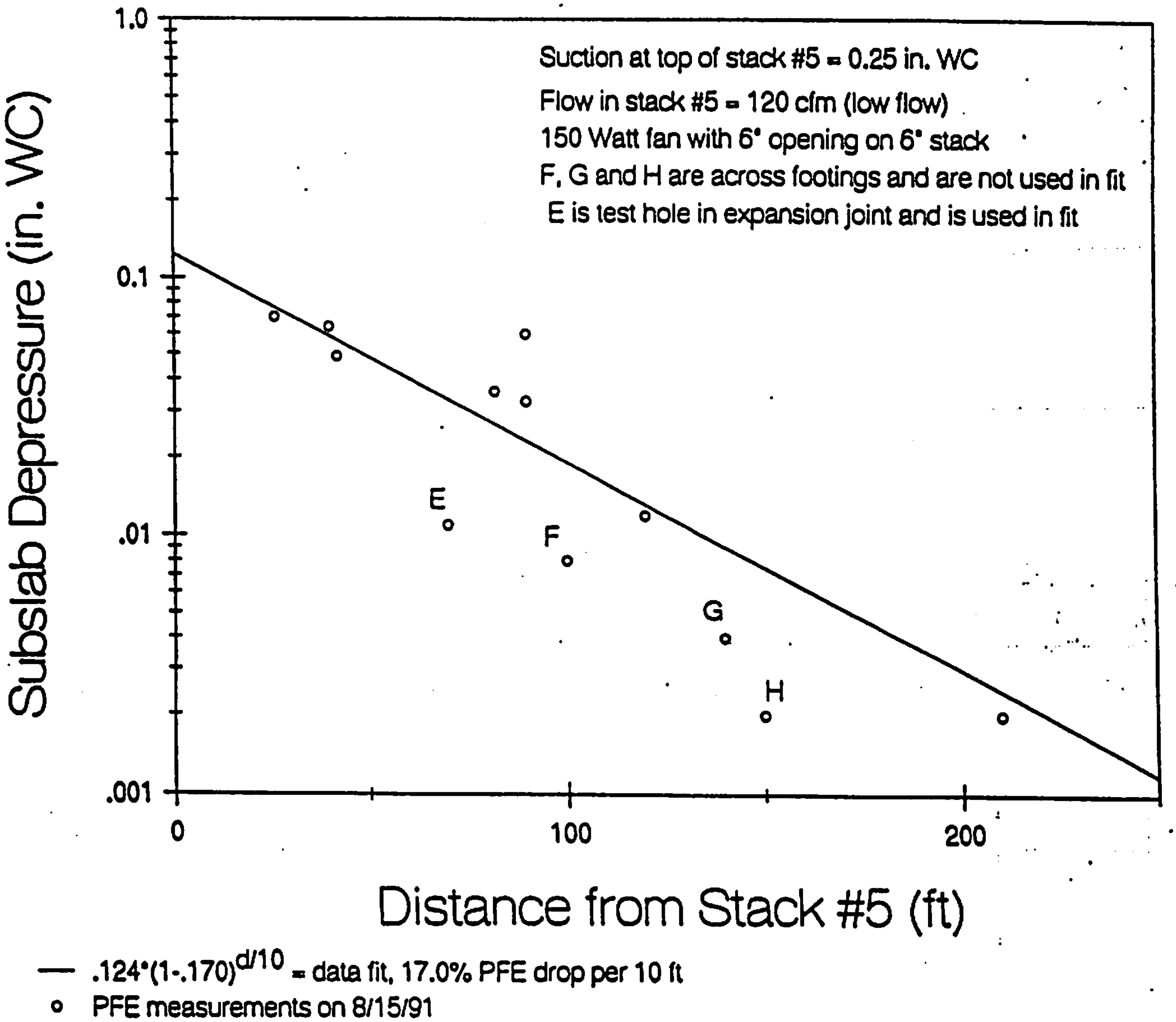

Figure 4 - Desmares Stack 5 Low Flow PFE Plot

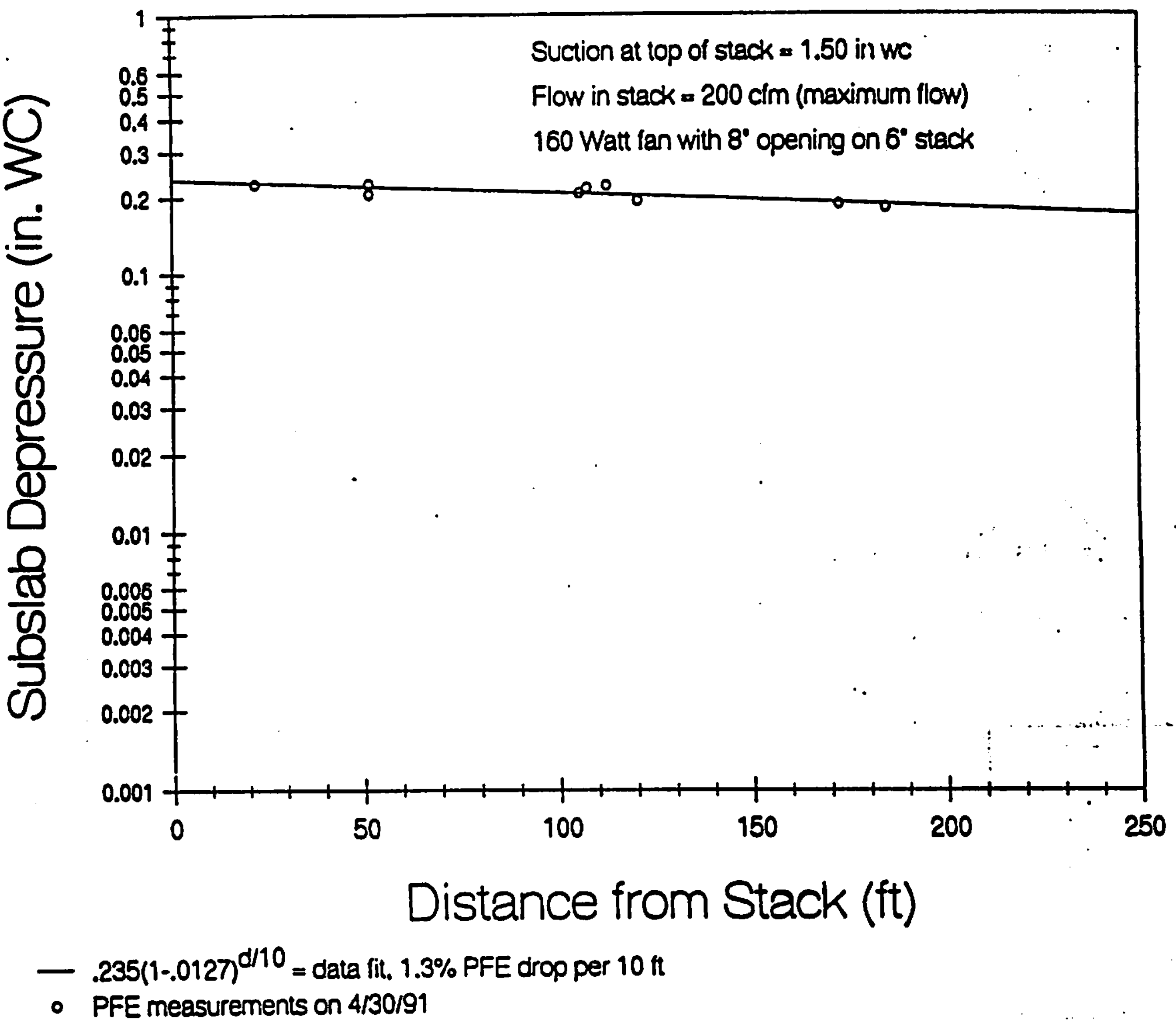

Figure 5 - Johnson City Stack PFE Plot