·#5155

IN-91-12-1 (RP-594)

REPEATABILITY AND REPRODUCIBILITY OF FAN PRESSURIZATION DEVICES IN MEASURING BUILDING AIR LEAKAGE

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ABSTRACT

Infiltration of outdoor air accounts for 20% to 50% of house energy losses during a heating season. Predicting air infiltration is the least accurate of all building heat loss calculations due to variations in house construction and the tightness of fit of the building components. The air-leakage characteristics of a house can be determined by several experimental means, perhaps the most convenient being a fan pressurization device (FPD), or so-called "blower door." While there are accepted standards for how the leakage tests are to be conducted and the results analyzed, there are no similar standards for the construction of the FPDs themselves. The sales volume of FPDs does not represent a large market, but state and local building standards may soon specify their use for code compliance, so an understanding of their accuracy is needed to validate their results.

This test used four different FPDs with three different operators to conduct round-robin tests on four different houses according to accepted test standards. The test results were analyzed for significant trends using a standard procedure for interlaboratory test programs. The results indicate that the extrapolation of test results to a house pressure of 4 Pa produced a 95% reproducibility interval of ±23.5% when averaged for all four test houses. At that condition, the impact of the operators was less than ±5%. At 50 Pa house pressure, these figures were ±7.5% and ±2%, respectively. The large interval at 4 Pa is largely a function of the statistical relationships when extrapolating far beyond the experimental measurements, as well as an effect of the less accurate low-pressure measurements being given greater weighting in the least-squares method.

INTRODUCTION

Several methods are in current use to measure air infiltration rates into existing houses. The tracer gas method has been used perhaps the longest, where CO, SF_6, or some other inert gas is introduced into the space and an analysis of concentration vs. time yields a volume change rate. The tracer gas method yields results that are dependent on the weather conditions that existed when the test was conducted and can be affected by occupant activity if they are present. To assess the infiltration characteristics of the structure over a range of weather conditions, the tracer gas tests must be conducted during that range of weather conditions. In the late 1970s, fan pressurization devices (FPDs) were developed to measure the air-leakage characteristics of houses. These so-called "blower doors" were initially used for energy auditing work in determining the sources of air leakage and estimating the magnitude of its reduction due to retrofit measures. A lot of work was done to correlate FPD and tracer gas results so the FPDs could be used to estimate actual energy savings due to natural air infiltration reduction (Meier 1986). A simple model was developed that incorporates the FPD results to compute an "effective leakage area" (ELA), or the size of an orifice that would produce the same flow at 4 Pa house pressure differential with an assumed flow coefficient of 1.0 (Sherman and Grimsrud 1980). A similar equivalent leakage area is defined in Canada using a 10 Pa pressure differential and a flow coefficient of 0.611 (CGSB 1986). The methods are outlined in the *ASHRAE Fundamentals* (ASHRAE 1989). FPDs are extremely attractive to use in conservation retrofit applications, since tests can be completed in a half-hour and the hardware usually includes a small computer with which to calculate energy savings on site due to conservation measures.

While much of the HVAC industry has accepted the FPD as a standard means of estimating air infiltration, there have been longstanding uncertainties about their accuracy (Persily 1983; Persily 1984; Persily and Grot 1985; Gadsby and Harrje 1985; duPont 1986; Dickinson and Feustel 1986a). There are standards in both the United States and Canada that specify proper procedures to follow in conducting FPD tests (ASTM 1987; CGSB 1986). However, most FPD operators are at the technician level and likely have had little formal training in air infiltration calculations. The ease of using the small computers may make any result that they produce seem perfectly valid. In addition to the obvious impact of ambient wind, differences in temperature and/or moisture content of the structural components have been speculated to play a role in causing significant differences in measured air leakage (Warren and Web 1980; Persily 1982; Harrje 1984; Kim and Shaw 1984; Nagda et al. 1985; Dickinson and Feustel 1986b). DuPont (1986) notes that some researchers found differences of 24% to 74% in ELA between measurements made with wind speeds of 5 to 10 mph and measurements made with no wind pressure whatsoever. However, these differences were reduced to 1% to 10% when both pressurization and depressurization tests were made and averaged.

A final cause for uncertainty has to do with the construction of the FPDs themselves. There are no standards for the actual construction of the devices, so the small manufacturers utilize materials and techniques that are readily available, cost-effective, and easy to work with. The early FPDs measured flow using fan rpm calibration curves, but this type has generally given way to fans with calibrated shrouds utilizing pitot taps. However, every manufacturer uses different designs and calibrates its units

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in different facilities, further increasing the likelihood of performance differences.

OBJECTIVE

The objective of this project was to determine the repeatability and reproducibility of air leakage tests with different FPDs and the effect of the operator on the results. The work was performed in an ASHRAE-sponsored project, 594-RP, and was sponsored by TC 4.3, Ventilation Requirements and Infiltration. The work statement called for four FPDs to be used by three operators, performing three replications of tests on four different houses. The tests were conducted according to *ASTM Standard E779-87, Standard Test Method for Determining Air Leakage by Fan Pressurization* (ASTM 1987). The analysis of results was performed according to *ASTM Standard E691-79, Standard Practice for Conducting an Interlaboratory Test Program to Determine the Precision of Test Methods* (ASTM 1979). The round-robin nature of the test was designed to provide useful information on differences in measurements attributable to both the operator and the FPD device.

METHODS AND PROCEDURES

The four houses used in this study ranged in age from 4 to 22 years and were from 1,900 to more than 3,100 square feet in size. Two houses were all electric with air-source heat pumps, while the other two had forced-air natural-draft gas furnaces with gas water heaters. The only unique feature of any of the houses was a whole-house attic fan in the hallway of one. The damper blades of that fan were held shut during testing to minimize any impact on the test results. Three of the houses had finished lower levels, so basement doors were left open. Prior to each day's testing sequence, the project supervisor inspected all doors and windows to ensure that they were not changed from the previous test conditions. This was done so that all the houses would be in apparently identical conditions from one day of testing to the next, so that any differences in results could be attributable only to the FPDs or their operators. No control tests were performed on the houses to guarantee that no changes had occurred in the houses during the testing interval. The outdoor temperature for all 144 tests was between a high of 93°F and a low of 66°F, with the vast majority of tests being conducted at outdoor temperatures between 75°F and 85°F. Indoor to outdoor temperature differences were negligible, especially after the first FPD test was complete. Two houses had occupants present during the FPD tests, while the occupants were not present in the other two houses. The houses are identified as houses 1, 2, 3, and 4.

Four FPDs were borrowed from four different manufacturers who were willing to participate in the testing program. Three of the four units were new and one was slightly used. They came with standard instructional materials and calibration information for the fans. Small computers were not requested, since all calculations were to be performed at one time later on, rather than individually in the field. One of the FPDs did not use pitot taps in the fan shroud to measure flow; instead, it had a pressure tap on the sealed electric motor housing. The motor rotor would generate a small pressure that was related to its fan speed (and, hence, flow rate). The fan of this unit was custom calibrated, with the calibration constants marked on the fan and in the operator's manual. Two of the units had molded fan inlet shrouds shaped like nozzles, while the third unit's fan housing created an orifice-type opening that was used for flow measurement. The individual FPDs are identified as W, X, Y, and Z.

The operators were from different backgrounds and had never conducted FPD tests before. Operator A was an extension engineer who specialized in farm safety and home weatherization. Operator B was retired from the Navy and had worked as a technician for about eight years after retirement. Operator C was a technician who worked mostly on farm projects but was also skilled in woodworking and general instrumentation. Their educational backgrounds varied from a high school diploma to a master's degree and their ages from the mid-40s to the mid-50s. Since none of these operators was familiar with FPDs, two trainers from a nonprofit agency in Ohio were hired to conduct a two-day training session on air infiltration fundamentals and hands-on FPD operating techniques and flow analysis. These trainers instruct all Community Action Agency personnel within the state who are involved in state-run weatherization programs, and they provided the same instructional short course that they give to service groups that use FPDs in low-income weatherization programs. The operators are identified by the designations A, B, and C.

The combination of three operators using four FPDs making three replications gives a total of 36 tests that were conducted on each of the four houses. While the ASTM standard does not address repeated tests, it was desirable to perform all tests on an individual house in as short a time frame as possible to avoid any possible temperature or moisture complications, as cited earlier. In addition, conducting tests when the mean wind speed was less than 5 mph was also necessary to prevent any significant wind effects. With the wind speed as a limiting factor, house 1 testing was completed in nine days while all the other houses were completed within seven days or less. The test program was not intended to demonstrate all the possible ways that FPDs can be misapplied, so the principal investigator oversaw all FPD tests to ensure that the units were properly installed. Consequently, all results are for tests run according to the manufacturers' specifications and the ASTM standard. To guard against any unintentional bias in tests due to time of day and to force the operators to completely disassemble each unit between tests, the FPDs were used in a random sequence given in Table 1. The operator/FPD combination was assigned a number and a random number generator was used to specify the test sequence. Operator A conducted the first test using FPD Z, then operator C used FPD W, and so on. This same sequence was used for each replication set, so all tests were not completely random, but any day-to-day effects would be evenly distributed between the FPDs and operators. Each test normally took from 20 to 30 minutes, and, in the interest of saving time, the principal investigator or one of

TABLE 1
Random Test Sequence for One Repetition

	OPERATOR		
FPD	A	B	C
W	11	3	2
X	8	5	7
Y	4	9	10
Z	1	6	12

the nontesting operators would disassemble the just-completed FPD while the next operator would begin setting up the FPD for his test. The operators filled out the test form shown in Figure 1, including the pertinent times, temperatures, and wind speed. Wind speed was measured with a hand-held anemometer and was generally measured 30 to 50 feet away from the house over a 30- to 60-second time period at the beginning and end of each test. The principal investigator recorded wind direction in a log book from visual observations and knowing the orientation of each house. He also monitored wind speed, and if he judged that it averaged 5 mph, all tests were halted for the day. Under these mild wind conditions, there were wind bursts where the speed peaked to 7 or 8 mph for a few seconds and then was nearly calm for 15 or 20 seconds. Such situations can affect the pressure readings of the FPDs due to the stagnation pressure on one side of the house and the wake on the other, and the operators were instructed to wait for such pressure fluctuations to dissipate before taking readings. When tests were halted because of the wind, testing was resumed on a later day where it had left off, without repeating any of the tests that were completed under acceptable wind conditions.

Several steps were taken to prevent any bias from entering into the results. The operators turned over their data sheets to the principal investigator immediately after completing their tests. Data taken by one operator were not seen by the other operators. No correlations were computed for the data in the field, so the operators had no feedback on how good or bad their numbers were. The principal investigator inspected each data sheet after it was turned over for consistent data trends. Occasionally an obviously erroneous reading was observed, such as a reading of 150 instead of 250, and it would be noted to delete that data point. The data points omitted in this manner were less than 0.3% of all pressure readings taken. No data were deleted after the correlations were computed simply because it made for a poor correlation. In this regard, the data-recording process differed from what is likely the standard procedure in the field of inspecting the data by running a correlation to check for goodness of fit. However, this trade-off was considered acceptable, so that the operators did not become familiar with each other's readings and introduce bias in some way. Barometric pressure readings were filled in afterward by the principal investigator using National Weather Service hourly readings from the local airport. If any peculiarities arose during a test, the principal investigator would note them on the comments section of the data page or in a log book that was kept on the field tests.

BLOWER DOOR TEST DATA FORM
ASHRAE RESEARCH PROJECT RP-594

OPERATOR CODE: A B C HOUSE CODE: 1 2 3 4

BLOWER DOOR CODE: W X Y Z

START TIME ____ DATE ________

BAROMETRIC PRESSURE ____ WIND SPEED ______MPH

INDOOR TEMPERATURE ____F OUTDOOR TEMPERATURE ____F

DEPRESSURIZATION TEST		PRESSURIZATION TEST	
HOUSE VACUUM (Pa)	FLOW READING Units___	HOUSE PRESSURE (Pa)	FLOW READING Units___
60		60	
50		50	
40		40	
30		30	
25		25	
20		20	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

INDOOR TEMPERATURE ____F OUTDOOR TEMPERATURE ____F

WIND SPEED _____MPH STOP TIME ____________

COMMENTS________________________________

Figure 1 Data sheet used in all tests

RESULTS

Three FPDs used correlation equations to convert a pressure reading to flow rate, while one unit had a pressure gauge already calibrated in flow units. The same density correction factor, based on indoor and outdoor temperatures, was specified by all four manufacturers and used for all FPDs:

$$Q_{corr} = Q_{meas} \sqrt{\frac{T_{o,abs}}{T_{i,abs}}} \qquad (1)$$

where the temperatures T_i and T_o were measured inside and outside the house and expressed in absolute Rankine or Kelvin. When the leakage flow rates are converted to equivalent flow rates, as if the tests had been conducted at standard temperature and pressure conditions, the barometric pressure term disappears in the density correction and hence was not found in Equation 1. This is the procedure used in the calculation of ELA and is the form used by each of the FPD manufacturers in the computer software that they provided. The corrected flow rates and house pressures were input to a BASIC program written to determine a least-squares regression curve of the form, $Q = C(\Delta P^n)$, using logarithms of both house pressure and flow rate. Table 2 shows the computed results for one such test for FPD W, operator A, replication 1, house 1. The depressurization and pressurization test data were treated separately and then combined for comparison. A 95% confidence interval was also computed for each pressure point and expressed as a percent. In addition, the flow rates at standard house pressures of 4, 10, 25, and 50 Pa were computed using the regression coefficient and exponent. The computed flow rates at the standard pressures were later used in the statistical analyses.

To illustrate how the FPD data appear on a log-log plot of flow vs. pressure, Figure 2 shows the test from Table 2 where the depressurization and pressurization data are shown separately. It is not uncommon for these two tests to produce measurable differences when there are backflow dampers in appliance vents or other leakage cracks that change size when under pressure vs. a vacuum. Since the FPD manufacturers seem to assume that most tests will be depressurization tests, it is possible that fan calibrations may be slightly different in the pressurization mode. Many of the pairs of tests did not have this much deviation between the two tests, especially in the houses with fewer vents or larger total flow rates. Figure 3 shows the relative scatter observed in the three replication tests for this

TABLE 2
Regression Analysis of One FPD Test

HOUSE 1 OPERATOR A BLOWER DOOR W

DEPRESSURIZATION REPLICATION NO. 1

PRESSURE EXPONENT - n = 0.7121
FLOW COEFFICIENT - C = 108.4
CORRELATION COEFFICIENT - R^2 = 0.9803
NUMBER OF DATA POINTS = 13

COMPUTED RESULTS AND ERROR ANALYSIS

DEL P (Pa)	FLOW (cfm)	FLOW CALC	95% CONF.	PERCENT
59	1837	1977	98	5.0
51.5	1866	1795	77	4.3
42.5	1569	1566	54	3.5
29	1177	1193	37	3.1
25.5	1081	1088	37	3.4
20	827	915	41	4.4
13.5	692	692	46	6.6
20	974	915	41	4.4
26	1120	1103	37	3.3
30.5	1266	1236	37	3.0
40	1569	1499	49	3.3
50	1820	1758	73	4.1
58	1900	1954	95	4.9

COMPUTED FLOW RATES AT STANDARD PRESSURES

4		291	42	14.4
10		559	47	8.5
25		1073	37	3.5
50		1758	73	4.1

HOUSE 1 OPERATOR A BLOWER DOOR W

PRESSURIZATION REPLICATION NO. 1

PRESSURE EXPONENT - n = 0.6723
FLOW COEFFICIENT - C = 150.2
CORRELATION COEFFICIENT - R^2 = 0.9885
NUMBER OF DATA POINTS = 13

COMPUTED RESULTS AND ERROR ANALYSIS

DEL P (Pa)	FLOW (cfm)	FLOW CALC	95% CONF.	PERCENT
60	2400	2355	85	3.6
46.5	1902	1984	54	2.7
38.5	1692	1748	39	2.2
32	1492	1543	32	2.1
24	1277	1272	32	2.5
19.5	1055	1106	35	3.2
14	875	885	40	4.5
20	1172	1125	35	3.1
26	1389	1342	31	2.3
30	1548	1478	31	2.1
42	1902	1853	45	2.4
50.5	2067	2097	62	3.0
58	2328	2302	80	3.5

COMPUTED FLOW RATES AT STANDARD PRESSURES

4		381	39	10.2
10		706	42	6.0
25		1307	32	2.4
50		2083	61	2.9

HOUSE 1 OPERATOR A BLOWER DOOR W

COMBINED DEPRESS. AND PRESS. REPLICATION NO. 1

PRESSURE EXPONENT - n = 0.6908
FLOW COEFFICIENT - C = 128.2
CORRELATION COEFFICIENT - R^2 = 0.8997
NUMBER OF DATA POINTS = 26

COMPUTED RESULTS AND ERROR ANALYSIS

DEL P (Pa)	FLOW (cfm)	FLOW CALC	95% CONF.	PERCENT
59	1837	2144	154	7.2
51.5	1866	1952	121	6.2
42.5	1569	1709	86	5.0
29	1177	1313	58	4.4
25.5	1081	1201	59	4.9
20	827	1016	65	6.4
13.5	692	774	74	9.5
20	974	1016	65	6.4
26	1120	1217	58	4.8
30.5	1266	1359	59	4.3
40	1569	1639	78	4.7
50	1820	1913	114	6.0
58	1900	2119	150	7.1
60	2400	2169	159	7.3
46.5	1902	1819	100	5.5
38.5	1692	1597	73	4.6
32	1492	1405	60	4.3
24	1277	1152	60	5.2
19.5	1055	998	65	6.6
14	875	794	73	9.2
20	1172	1016	65	6.4
26	1389	1217	58	4.8
30	1548	1344	58	4.4
42	1902	1696	84	5.0
50.5	2067	1926	117	6.1
58	2328	2119	150	7.1

COMPUTED FLOW RATES AT STANDARD PRESSURES

4		334	69	20.8
10		629	77	12.2
25		1185	59	5.0
50		1913	114	6.0

operator conducting the same depressurization test. Two of the data sets happen to produce nearly identical regression constants, while the third is noticeably different. Differences as large as these were fairly common among all FPDs and operators. Figure 4 shows the regression results when combining the three depressurization replications for each operator using the same FPD. All three curves intersect nearly an identical point at the high-pressure end, but they differ by as much as 20% at the 4-Pa end.

The ASTM E691 statistical analysis procedure calls for the data to be tabulated in certain ways so that averages and deviations can be computed to separate out the random errors caused by the FPDs from the effects of the operators. Table 3 gives an overall summary of the 4 Pa computed results for the depressurization tests for all FPDs, operators, and houses. Similar analyses were conducted for the 4, 10, 25, and 50 Pa results for the depressurization, pressurization, and combined tests for a total of 12 data sets. Only the 4 Pa depressurization results will be shown

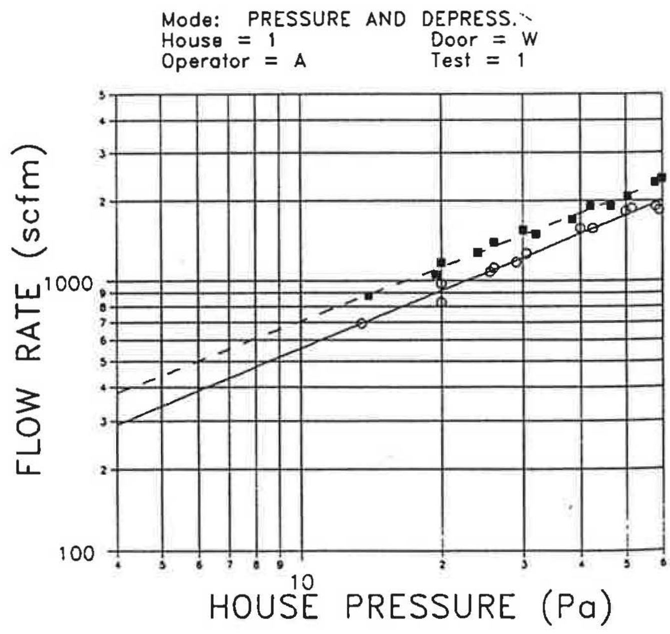

Figure 2 *Linearized plot of FPD measurements on log-log scale showing pressurization and depressurization data*

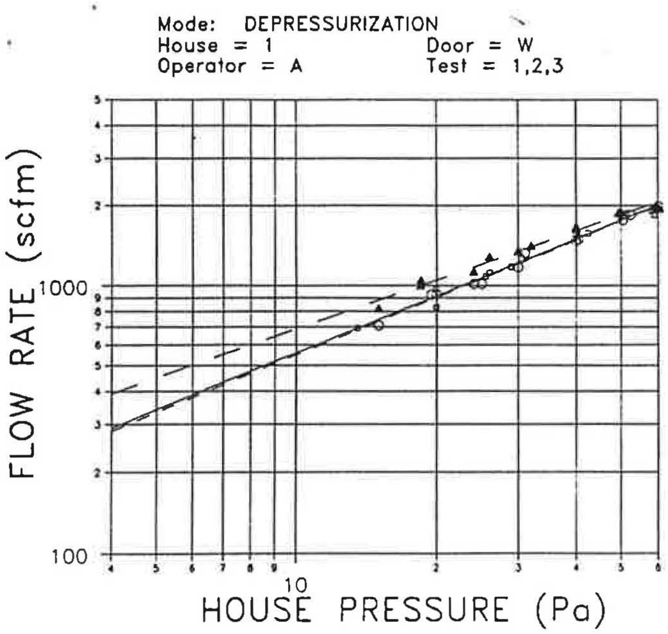

Figure 3 *Three replication tests with curve-fit lines*

TABLE 3
Linear Regression Flow Rates (corrected) Depressurization Test at 4 Pa

TABLE 3 LINEAR REGRESSION FLOW RATES 4 Pa DEPRESSURIZATION DATA

FPD/OPERATOR	HOUSE 1 CFM	HOUSE 2 CFM	HOUSE 3 CFM	HOUSE 4 CFM
W/A	291	786	405	851
	284	790	450	809
	392	808	403	828
W/B	313	641	392	810
	393	851	405	696
	440	650	376	816
W/C	311	709	377	1012
	367	728	451	808
	359	724	383	782
X/A	326	711	356	707
	325	615	411	767
	299	711	335	779
X/B	319	702	367	728
	300	682	381	768
	285	653	390	733
X/C	340	679	384	734
	318	753	353	763
	318	763	306	729
Y/A	287	771	270	904
	285	805	247	905
	252	816	265	837
Y/B	270	768	275	917
	296	811	326	947
	243	826	305	1041
Y/C	223	867	293	1011
	289	804	301	904
	260	792	266	927
Z/A	498	876	502	893
	613	852	502	985
	495	900	504	922
Z/B	490	917	506	967
	591	864	449	981
	462	875	462	916
Z/C	549	687	462	807
	449	908	503	832
	468	856	438	822
COL. AVERAGE	361.1	776.4	383.4	851.1
STAND. DEV.	102.0	82.9	77.2	95.5

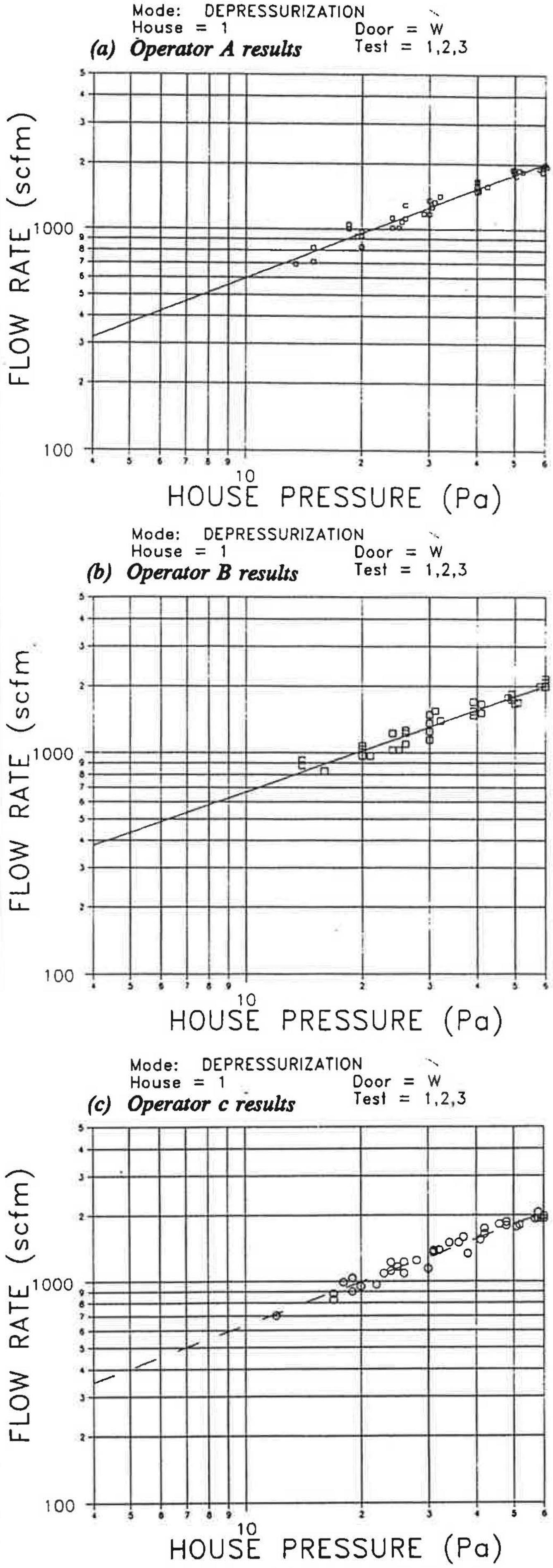

Figure 4 *Comparison of three sets of data for one operator*

in this paper due to space limitations. The complete results for all test conditions can be found in Murphy et al. (1990). Table 4 shows these same results broken down into the operator vs. FPD format that is needed for the statistical analysis for each house. Table 5 gives the cell average (of the three replications) results for comparison between the FPDs and the operators. Table 6 shows the standard deviation within the replication results, and Table 7 gives the deviations from the average for all three operators.

At this point it is appropriate to describe the different deviations that were computed to separate out the operator deviations from the FPD deviations. Figure 5 shows schematically the results of one set of tests. The cell

TABLE 4
Arrangement of Replication Test Results Into Operator vs. FPD Format

HOUSE 1

	FPD W	FPD X	FPD Y	FPD Z
OPER. A	291	326	287	498
	284	325	285	613
	392	299	252	495
OPER. B	313	319	270	490
	393	300	296	591
	440	285	243	462
OPER. C	311	340	223	549
	367	318	289	449
	359	318	260	468
COL. AVG.	350.0	314.4	267.2	512.8
STAN. DEV	53.4	16.8	24.6	58.3

HOUSE 2

	FPD W	FPD X	FPD Y	FPD Z
OPER. A	786	711	771	876
	790	615	805	852
	808	711	816	900
OPER. B	641	702	768	917
	851	682	811	864
	650	653	826	875
OPER. C	709	679	867	687
	728	753	804	908
	724	763	792	856
COL. AVG.	743.0	696.6	806.7	859.4
STAN. DEV	71.4	46.3	29.8	68.6

HOUSE 3

	FPD W	FPD X	FPD Y	FPD Z
OPER. A	405	356	270	502
	450	411	247	502
	403	335	265	504
OPER. B	392	367	275	506
	405	381	326	449
	376	390	305	462
OPER. C	377	384	293	462
	451	353	301	503
	383	306	266	438
COL. AVG.	404.7	364.8	283.1	480.9
STAN. DEV	28.3	31.6	24.7	27.6

HOUSE 4

	FPD W	FPD X	FPD Y	FPD Z
OPER. A	851	707	904	893
	809	767	905	985
	828	779	837	922
OPER. B	810	728	917	967
	696	768	947	981
	816	733	1041	916
OPER. C	1012	734	1011	807
	808	763	904	832
	782	729	927	822
COL. AVG.	823.6	745.3	932.6	902.8
STAN. DEV	82.9	24.4	61.2	69.2

TABLE 5
Averages of the Three Replication Tests

HOUSE 1

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	322	317	275	535	362.3
OPER. B	382	301	270	514	366.8
OPER. C	346	325	257	489	354.3
COL. AVG.	350.0	314.4	267.2	512.8	361.1

HOUSE 2

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	795	679	797	876	786.8
OPER. B	714	679	802	885	770.0
OPER. C	720	732	821	817	772.5
COL. AVG.	743.0	696.6	806.7	859.4	776.4

HOUSE 3

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	419	367	261	503	387.5
OPER. B	391	379	302	472	386.2
OPER. C	404	348	287	468	376.4
COL. AVG.	404.7	364.8	283.1	480.9	383.4

HOUSE 4

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	829	761	882	933	848.9
OPER. B	774	743	968	955	860.0
OPER. C	867	742	947	820	844.3
COL. AVG.	823.6	745.3	932.6	902.8	851.1

TABLE 6
Standard Deviations for Each FPD/Operator Combination

HOUSE 1

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER .A	60.4	15.3	19.7	67.3	40.7
OPER. B	64.2	17.0	26.5	67.9	43.9
OPER. C	30.3	12.7	33.1	53.1	32.3
s_r	53.8	15.1	27.0	63.1	39.8

HOUSE 2

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	11.7	55.4	23.5	24.0	28.7
OPER. B	118.7	24.6	30.1	28.0	50.4
OPER. C	10.0	45.9	40.3	115.5	52.9
s_r	69.1	43.9	32.0	70.0	53.8

HOUSE 3

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	26.6	39.2	12.1	1.2	19.8
OPER. B	14.5	11.6	25.6	29.9	20.4
OPER. C	41.1	39.3	18.3	32.9	32.9
s_r	29.5	32.7	19.5	25.7	26.8

HOUSE 4

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	21.0	38.6	39.0	47.0	36.4
OPER. B	67.6	21.8	64.7	34.2	47.1
OPER. C	126.0	18.4	56.3	12.6	53.3
s_r	83.4	27.7	54.4	34.4	50.0

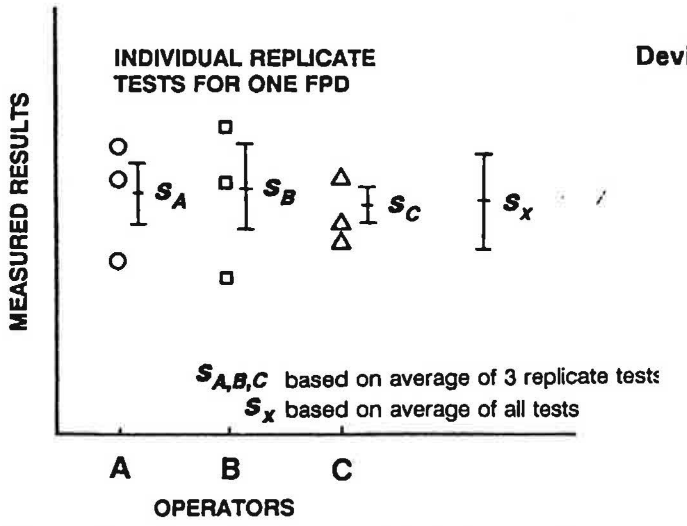

Figure 5 *Example of standard deviations used in statistical analyses*

standard deviations S_A, S_B, S_C are those found in Table 6. The quantity S_r at the bottom of each house data set in Table 6 is the root-mean square of the three individual cell standard deviations for one FPD and is called the "pooled standard deviation." It is computed by the relationship

$$S_r = \sqrt{\frac{\sum S_i^2}{p}} \qquad (2)$$

where the S_i values are the cell standard deviations for each operator (S_A, S_B, S_C) using that particular FPD, and p is the number of operators, in this case three. S_r accounts for the repeatability of that FPD, since it must be assumed that each operator is personally consistent with each FPD. The quantity S_x in Table 7 is a simple standard deviation using all measurements from all operators for a given FPD. S_x is computed by the equation

$$S_x = \sqrt{\frac{\sum (\bar{x}_i - \bar{x})^2}{p-1}} \qquad (3)$$

where the quantity in parentheses represents the difference between the replication average for a given operator and the overall average for all operators. The standard deviation due to the operators, S_{op}, is separated out by the relationship

$$S_{op} = \sqrt{S_x^2 - \frac{S_r^2}{n}} \qquad (4)$$

where n is the number of replications of each FPD/operator test (each operator conducted three tests with each FPD in every house). If the quantity inside the radical is negative, the value of S_{op} is set equal to zero. Thus, one can equate S_r with the repeatability due to just the variations in FPD performance and S_{op} with just the variation introduced by the different operators. Obviously, if a leakage test were conducted with a given FPD and an arbitrarily appointed operator, the standard deviation or variance would have to incorporate both of these effects. The overall reproducibility

TABLE 7
Deviations from Average for Each FPD/Operator Combination

HOUSE 1

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	-27.7	2.2	7.4	22.6	1.1
OPER. B	32.0	-13.1	2.4	1.6	5.7
OPER. C	-4.3	10.9	-9.9	-24.1	-6.9
s_x	30.1	12.2	8.9	23.4	18.6

HOUSE 2

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	51.7	-17.6	-9.3	16.6	10.3
OPER. B	-29.0	-17.6	-5.0	25.9	-6.4
OPER. C	-22.7	35.1	14.3	-42.4	-3.9
s_x	44.9	30.4	12.6	37.1	31.2

HOUSE 3

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	14.7	2.6	-22.4	21.8	4.1
OPER. B	-13.7	14.6	18.9	-8.6	2.8
OPER. C	-1.0	-17.1	3.6	-13.2	-6.9
s_x	14.2	16.0	20.9	19.0	17.5

HOUSE 4

	FPD W	FPD X	FPD Y	FPD Z	AVG.
OPER. A	5.8	5.7	-50.6	30.6	-2.1
OPER. B	-49.6	-2.3	35.8	51.9	8.9
OPER. C	43.8	-3.3	14.8	-82.4	-6.8
s_x	46.9	4.9	45.0	72.2	42.3

deviation, S_R, which combines these two effects, is simply the square root of the sum of the individual variances:

$$S_R^2 = S_r^2 + S_{op}^2 \, . \qquad (5)$$

S_R is different from S_x in that S_R combines the variability of all the FPDs, while S_x accounts for each FPD separately. It is customary to determine the interval (± % of reading) that is likely to contain a specified percentage of all readings. At the 95% level, this interval, I_{95}, is related to the standard deviation by the approximate relationship

$$I_{95} = 2\sqrt{2}\ V = 2.83\ V \qquad (6)$$

where V would be the appropriate standard deviation S expressed as a percentage of the average. The 2.83 approximates the tabular value for 95% probability levels and is considered acceptable by ASTM E691. Table 8 summarizes the values of S_r, S_{op}, and S_R and also expresses them in percentage terms (V_r, V_{op}, and V_R). The corresponding 95% intervals for FPD repeatability, operator error, and overall reproducibility are summarized in Tables 9 through 11 for all 12 sets of tests. The test notation in these tables uses D to denote depressurization tests, P for pressurization tests, and C for combined pressurization and depressurization. The 4, 10, 25, and 50 correspond to the house pressure differentials in Pascal at which the flow rates were computed.

TABLE 8
Standard Deviations for FPD Repeatability, Operator Error, and Overall Reproducibility

HOUSE 1

FPD	AVG FLOW (cfm)	S_r (cfm)	S_{op} (cfm)	S_R (cfm)	V_r (%)	V_{op} (%)	V_R (%)
W	350.0	53.83	0.00	53.83	15.38	0.0	15.38
X	314.4	15.12	8.45	17.32	4.81	2.69	5.51
Y	267.2	26.98	0.00	26.98	10.09	0.0	10.09
Z	512.8	63.12	0.00	63.12	12.31	0.0	12.31

HOUSE 2

FPD	AVG FLOW (cfm)	S_r (cfm)	S_{op} (cfm)	S_R (cfm)	V_r (%)	V_{op} (%)	V_R (%)
W	743.0	69.12	20.48	72.09	9.30	2.76	9.70
X	696.6	43.91	16.79	47.01	6.30	2.41	6.75
Y	806.7	32.04	0.00	32.04	3.97	0.00	3.97
Z	859.4	70.02	0.00	70.02	8.15	0.00	8.15

HOUSE 3

FPD	AVG FLOW (cfm)	S_r (cfm)	S_{op} (cfm)	S_R (cfm)	V_r (%)	V_{op} (%)	V_R (%)
W	404.7	29.48	0.0	29.48	7.28	0.0	7.28
X	364.8	32.75	0.0	32.75	8.98	0.0	8.98
Y	283.1	19.49	17.61	26.27	6.88	6.22	9.28
Z	480.9	25.65	11.91	28.28	5.33	2.48	5.88

HOUSE 4

FPD	AVG FLOW (cfm)	S_r (cfm)	S_{op} (cfm)	S_R (cfm)	V_r (%)	V_{op} (%)	V_R (%)
W	823.6	83.43	0.0	83.43	10.13	0.0	10.13
X	745.3	27.69	0.0	27.69	3.71	0.0	3.71
Y	932.6	54.40	32.26	63.24	5.83	3.46	6.78
Z	902.8	34.36	69.41	77.45	3.81	7.69	8.58

SUMMARY AND CONCLUSIONS

The 95% interval tables show clearly that the errors introduced by differences in operators is very small compared to the repeatability of the FPDs themselves. In addition, these intervals decrease by nearly a factor of 5 in going from the 4-Pa level to the 50-Pa level. This dramatic decrease can be explained by two effects. The first has to do with the statistical relationships themselves. Persily and Grot (1985) note that the standard error, E_{Y_K}, of a predicted value using a least-squares fit is given by

$$E_{Y_K} = \sqrt{\frac{\sum_{i=1}^{N}(\hat{Y}_i - Y_i)^2}{N-2}}\sqrt{\frac{1}{N} + \frac{(X_K - \bar{X})^2}{\sum_{i=1}^{N}(X_i - \bar{X})^2}} \quad (7)$$

where (X_i, Y_i) is the ith set of N data pairs of $\ln(\Delta P)$ and $\ln(Q)$, $\bar{X}$ is the average of all the $\ln(\Delta P)$ terms, and the subscript K denotes the particular (X, Y) point of interest. The term $\hat{Y}$ represents the computed value of $\ln(Q)$ at the corresponding value of ΔP. Equation 7 shows that for values of X_K far from the average value of X, the standard error increases due to the second radical term. At values of X_K equal to the average X value, that term goes to

$$\sqrt{\frac{1}{N}}.$$

TABLE 9
FPD Repeatability Intervals at the 95% Level (±%)

HOUSE 1

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	43.5	13.6	28.6	34.8	30.1
P4	25.7	21.1	38.0	38.7	30.9
C4	26.7	9.6	29.4	22.8	22.1
D10	30.7	11.1	20.5	25.5	22.0
P10	14.6	12.6	24.1	27.3	19.7
C10	17.0	6.0	18.7	16.4	14.5
D25	18.2	9.7	14.7	16.6	14.8
P25	7.3	5.1	10.9	16.7	10.0
C25	8.1	4.1	9.6	10.4	8.1
D50	9.7	9.6	14.6	10.5	11.1
P50	11.0	4.3	5.2	10.3	7.7
C50	5.4	5.3	8.0	6.8	6.4

HOUSE 2

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	26.3	17.8	11.2	23.1	19.6
P4	23.3	10.2	33.5	25.6	23.1
C4	17.1	11.2	19.1	5.1	13.1
D10	18.4	12.0	7.2	15.3	13.2
P10	17.9	8.8	22.6	14.5	16.0
C10	12.1	7.9	12.2	3.7	9.0
D25	10.4	6.3	4.0	7.9	7.2
P25	13.4	9.1	12.5	5.5	10.1
C25	7.9	5.5	5.8	3.1	5.6
D50	4.8	3.3	4.0	6.2	4.6
P50	11.2	8.2	7.8	7.5	8.7
C50	6.2	5.1	2.9	3.5	4.4

HOUSE 3

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	20.6	25.4	19.5	15.1	20.1
P4	23.5	24.7	22.5	39.3	27.5
C4	17.4	14.3	16.5	24.5	18.2
D10	12.4	17.0	14.5	10.1	13.5
P10	15.4	16.3	11.7	27.6	17.8
C10	9.0	9.4	9.3	17.2	11.2
D25	5.2	8.7	10.9	6.3	7.8
P25	16.0	7.6	6.1	16.0	11.4
C25	7.2	4.3	5.4	10.4	6.8
D50	4.2	3.6	10.2	6.4	6.1
P50	22.3	1.7	11.8	7.9	10.9
C50	12.4	1.3	8.1	6.1	7.0

HOUSE 4

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	28.7	10.5	16.5	10.8	16.6
P4	32.7	21.6	18.0	24.9	24.3
C4	12.3	9.0	9.1	14.0	11.1
D10	19.2	7.4	12.6	7.7	11.7
P10	22.3	14.8	10.9	12.4	15.1
C10	8.0	6.1	6.7	7.0	6.9
D25	10.3	4.7	9.4	5.1	7.4
P25	12.5	8.1	5.1	4.5	7.6
C25	4.7	3.2	5.0	3.4	4.1
D50	4.6	3.4	8.0	4.3	5.1
P50	8.6	3.7	5.5	11.3	7.3
C50	5.1	1.8	4.3	6.9	4.5

TABLE 10
Operator Error Intervals at the 95% Level (±%)

HOUSE 1

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	0.0	7.6	0.0	0.0	1.9
P4	0.0	0.0	0.0	7.9	2.0
C4	0.0	0.0	0.0	6.0	1.5
D10	0.0	4.0	0.0	0.0	1.0
P10	0.0	0.0	0.0	0.0	0.0
C10	0.0	1.0	0.0	0.0	0.3
D25	0.0	0.0	0.0	0.0	0.0
P25	4.4	0.0	0.0	0.0	1.1
C25	0.0	0.0	0.0	0.0	0.0
D50	0.0	0.0	0.0	0.0	0.0
P50	0.0	0.0	2.7	0.0	0.7
C50	1.1	0.0	4.0	0.0	1.3

HOUSE 2

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	7.8	6.8	0.0	0.0	3.7
P4	10.9	0.0	0.0	0.0	2.7
C4	0.0	4.9	8.4	9.3	5.6
D10	3.8	4.4	0.0	0.0	2.0
P10	6.1	0.0	4.1	0.0	2.6
C10	0.0	1.9	5.8	4.6	3.1
D25	0.0	1.7	2.4	0.0	1.0
P25	0.0	0.0	4.7	0.0	1.2
C25	0.0	0.0	3.0	0.0	0.8
D50	1.7	0.0	4.4	5.5	2.9
P50	0.0	0.0	0.8	0.0	0.2
C50	0.0	0.0	0.8	2.8	0.9

HOUSE 3

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	0.0	0.0	17.6	7.0	6.2
P4	7.4	0.0	7.9	0.0	3.8
C4	0.0	6.3	12.8	0.0	4.8
D10	0.0	0.0	4.8	1.2	1.5
P10	3.4	0.0	5.2	0.0	2.1
C10	0.0	2.7	6.1	0.0	2.2
D25	1.6	0.0	0.0	0.0	0.4
P25	0.0	0.0	0.0	0.0	0.0
C25	1.2	0.0	0.0	0.0	0.3
D50	2.9	0.0	8.9	3.9	3.9
P50	0.0	3.2	0.0	0.0	0.8
C50	0.0	2.2	2.9	0.0	1.3

HOUSE 4

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	0.0	0.0	9.8	21.8	7.9
P4	0.0	11.9	2.7	0.0	3.6
C4	8.9	7.6	9.8	11.2	9.4
D10	0.5	0.0	0.0	14.2	3.7
P10	0.0	6.9	4.6	0.0	2.9
C10	7.0	4.6	5.7	7.0	6.1
D25	2.4	0.0	0.0	6.3	2.2
P25	0.0	0.0	4.0	4.9	2.2
C25	4.9	1.4	0.9	2.2	2.3
D50	2.8	0.0	0.0	0.0	0.7
P50	1.6	0.0	0.0	0.0	0.4
C50	3.1	0.0	0.0	0.0	0.8

TABLE 11
Overall Reproducibility Intervals at the 95% Level (±%)

HOUSE 1

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	43.5	15.6	28.6	34.8	30.6
P4	25.7	21.1	38.0	39.5	31.1
C4	26.7	9.6	29.4	23.6	22.3
D10	30.7	11.8	20.5	25.5	22.1
P10	14.6	12.6	24.1	27.3	19.7
C10	17.0	6.1	18.7	16.4	14.5
D25	18.2	9.7	14.7	16.6	14.8
P25	8.5	5.1	10.9	16.7	10.3
C25	8.1	4.1	9.6	10.4	8.1
D50	9.7	9.6	14.6	10.5	11.1
P50	11.0	4.3	5.9	10.3	7.9
C50	5.5	5.3	8.9	6.8	6.6

HOUSE 2

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	27.5	19.1	11.2	23.1	20.2
P4	25.7	10.2	33.5	25.6	23.7
C4	17.1	12.2	20.9	10.6	15.2
D10	18.7	12.7	7.2	15.3	13.5
P10	18.9	8.8	23.0	14.5	16.3
C10	12.1	8.1	13.5	6.0	9.9
D25	10.4	6.6	4.7	7.9	7.4
P25	13.4	9.1	13.4	5.5	10.3
C25	7.9	5.5	6.5	3.1	5.8
D50	5.1	3.3	5.9	8.2	5.7
P50	11.2	8.2	7.8	7.5	8.7
C50	6.2	5.1	3.0	4.5	4.7

HOUSE 3

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	20.6	25.4	26.3	16.6	22.2
P4	24.7	24.7	23.8	39.3	28.1
C4	17.4	15.6	20.9	24.5	19.6
D10	12.4	17.0	15.3	10.2	13.7
P10	15.7	16.3	12.8	27.6	18.1
C10	9.0	9.8	11.2	17.2	11.8
D25	5.4	8.7	10.9	6.3	7.9
P25	16.0	7.6	6.1	16.0	11.4
C25	7.3	4.3	5.4	10.4	6.9
D50	5.1	3.6	13.5	7.5	7.4
P50	22.3	3.7	11.8	7.9	11.4
C50	12.4	2.6	8.6	6.1	7.4

HOUSE 4

TEST	FPD W	FPD X	FPD Y	FPD Z	AVG.
D4	28.7	10.5	19.2	24.3	20.7
P4	32.7	24.6	18.2	24.9	25.1
C4	15.2	11.8	13.4	17.9	14.6
D10	19.2	7.4	12.6	16.1	13.8
P10	22.3	16.3	11.9	12.4	15.7
C10	10.6	7.6	8.8	9.9	9.2
D25	10.6	4.7	9.4	8.2	8.2
P25	12.5	8.1	6.5	6.6	8.4
C25	6.8	3.5	5.0	4.1	4.9
D50	5.4	3.4	8.0	4.3	5.3
P50	8.7	3.7	5.5	11.3	7.3
C50	6.0	1.8	4.3	6.9	4.8

The standard error thus produces an envelope about the least-squares line that is narrowest at the average X value and increasingly widens with X values greater or smaller than the average. The second radical in Equation 7 depends on the number as well as the distribution of the data points about the mean. For a given data set, the standard error varies only due to the distance that a chosen value of X_K is from the average X value. For the values of house pressure used in this test with 13 data points, the second radical term in Equation 7 has a value of about 1.38 at 4 Pa, 0.33 at 25 Pa, and 0.39 at 50 Pa. Thus, the standard error can be expected to be more than four times greater at 4 Pa than at 25 Pa but only about 20% greater at 50 Pa than at 25 Pa. This effect stems from the extrapolation to 4 Pa when the data points that generated the least-squares fit had an average of 33 Pa.

The second effect has to do with the expected accuracy of the equipment at low house pressure differentials. While large pressure differentials produce nearly full-scale gauge readings, and likely the most accurate readings, small pressure differentials produce the least accurate readings. These least accurate readings at the bottom end of the data range have a greater impact on "pivoting" the least-squares line up or down. The logarithmic transformation of the data for the linear least-squares curve fit compresses the upper end of the pressure range, giving the more accurate data points lesser weight in the least-squares calculation. This effect is unrelated to the increasing standard errors at low pressures due to the statistical relationships in Equation 7 and depends on many factors, such as outdoor wind speed, gauge and fan calibration accuracy, and operator technique.

Although Tables 9 through 11 demonstrate similar trends for all FPDs tested, FPD W had the largest repeatability intervals of the group, FPD X had the smallest, and FPDs Y and Z were in the middle. There was no simple explanation for this difference based on FPD construction or materials. All FPDs used the same type of pressure gauges and had smooth variable-speed fan controls. The best possible explanation for these differences is that FPD X had the gauges mounted on a freestanding tripod with hoses that allowed it and the operator to be well away from the fan. FPD W required the operator to actually move in front of the fan to adjust the fan speed and then move away from the fan to read the gauges. FPDs Y and Z required the operator to stand directly in front of the fan at all times while reading the gauges. Differences in flow readings were seen as the operator moved around the fan, so it is speculated that this effect accounts for some portion of the differences in repeatability demonstrated in all the test results.

Except for some of the house 1 results, all the reproducibility results (in Table 11) indicate that the depressurization tests were slightly more consistent than the pressurization tests. For example, the average of the 4 Pa depressurization reproducibilities for the four houses is ±23.4%, while it is ±27.0% for the pressurization data. The combined results are more consistent than either alone, averaging 17.9% for the 4-Pa data. However, an even better figure would probably be obtained if twice the number of data points were taken in the depressurization mode, since the combined results benefit the most from the greater number of points used in the calculations. Most FPD manufacturers suggest that all tests be done in the depressurization mode, and these results indicate that such tests do, in fact, produce somewhat more consistent results.

One final comparison is made to illustrate more clearly the relative differences that can be obtained from different FPDs and different operators. Tables 12 and 13 give percent deviations from the average (of all 36 tests) for houses 1 and 2 and are broken down by operator and by increasing house pressure differential. Table 12 (the tight house) gives quite large deviations for FPDs Y and Z, while the corresponding figures in Table 13 are much smaller. The trend of reduced deviation in going from low pressure (and flow) to high pressure is consistent among all operators. Figure 6 illustrates these results graphically. The trend of FPD Y giving results far below average for the tight house and well above average for the loose house can be explained by the fan calibration. The FPDs were

TABLE 12
Comparison of Percent Deviation vs. Pressure Differential for House 1 Depressurization Data

		HOUSE 1			
OPERATOR A - DEPRESSURIZATION DATA ONLY					
House ΔP (Pa)	Ave. Flow (cfm)	FPD W % Deviation	FPD X % Deviation	FPD Y % Deviation	FPD Z % Deviation
4	361	-10.8	-12.2	-23.8	48.2
10	651	-8.2	-7.9	-14.9	31.6
25	1184	-6.0	-4.0	-5.7	16.0
50	1870	-4.7	-1.4	1.6	4.9
OPERATOR B - DEPRESSURIZATION DATA ONLY					
4	361	5.8	-16.6	-25.2	42.3
10	651	2.6	-11.3	-17.5	28.8
25	1184	-1.1	-6.4	-9.5	15.6
50	1870	-4.1	-3.0	-3.4	6.1
OPERATOR C - DEPRESSURIZATION DATA ONLY					
4	361	-4.2	-10.0	-28.8	35.4
10	651	-3.1	-6.6	-18.5	25.3
25	1184	-2.8	-3.8	-7.5	15.1
50	1870	-3.0	-2.2	1.5	7.6
FPD % DEVIATIONS AVERAGED OVER ALL OPERATORS					
4	361	-3.1	-12.9	-26.0	42.0
10	651	-2.9	-8.6	-17.0	28.5
25	1184	-3.3	-4.7	-7.5	15.6
50	1870	-3.9	-2.2	-0.1	6.2

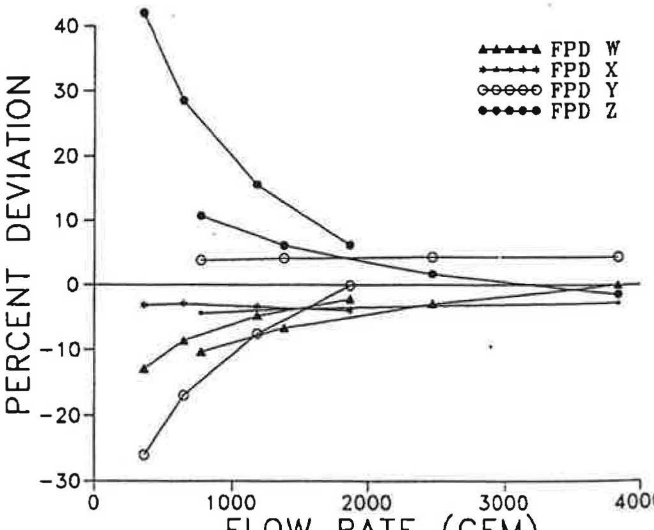

Figure 6 FPD percent deviation from average for houses 1 and 2

TABLE 13
Comparison of Percent Deviation vs. Pressure Differential for House 2 Depressurization Data

		HOUSE 2			
OPERATOR A - DEPRESSURIZATION DATA ONLY					
House ΔP (Pa)	Ave. Flow (cfm)	FPD W % Deviation	FPD X % Deviation	FPD Y % Deviation	FPD Z % Deviation
4	776	2.4	-12.5	2.7	12.8
10	1384	0.7	-8.3	4.2	7.0
25	2473	-1.1	-3.9	5.5	1.4
50	3838	-2.5	-0.5	6.4	-2.7
OPERATOR B - DEPRESSURIZATION DATA ONLY					
4	776	-8.0	-12.5	3.3	14.0
10	1384	-5.9	-8.0	3.2	7.7
25	2473	-3.7	-3.4	3.1	1.6
50	3838	-1.9	0.1	2.8	-2.9
OPERATOR C - DEPRESSURIZATION DATA ONLY					
4	776	-7.3	-5.7	5.7	5.2
10	1384	-6.0	-3.5	5.2	3.7
25	2473	-4.8	-1.3	4.6	2.2
50	3838	-4.1	0.3	4.0	1.1
FPD % DEVIATIONS AVERAGED OVER ALL OPERATORS					
4	776	-4.3	-10.3	3.9	10.7
10	1384	-3.7	-6.6	4.2	6.1
25	2473	-3.2	-2.9	4.4	1.7
50	3838	-2.8	-0.0	4.4	-1.5

calibrated in this project, but those results will be addressed at length in a future paper. Similarly, the FPD Z trend for house 2, going from well above average at the low-pressure end but below average on the high-pressure end, can also be explained by calibration effects.

In conclusion, the average 95% reproducibility interval for these four FPDs is about ±23.5% at 4 Pa depressurization house pressure differentials, where the effect of the operator on the reading averaged less than ±5%. This interval reduces to less than ±7.5% at 50 Pa with the operator contributing less than ±2% of the error. Because of the relatively small operator error, the overall reproducibility interval, which accounts for errors from both the FPD and the operator, was only slightly larger than the repeatability interval for just the FPDs. These results indicate that the ordinary use of FPDs by typical operators to determine envelope airtightness levels in existing houses may do little better than the ±25% accuracy usually expressed in infiltration computations, at least when the 4-Pa house pressure results are used in the calculation of ELA. Using results at 25 Pa or 50 Pa would reduce this error interval to ±10% or better.

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