

**IMPACT OF DUCT LEAKAGE PRESSURES ON THE SHAPE OF THE
DELTA Q CURVE**

JOHN W. ANDREWS

FEBRUARY 2002

**Prepared for:
Office of Building Technologies
State and Community Programs
U.S. Department of Energy
Washington, DC 20585**

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ABSTRACT

The question of whether and to what extent information on the pressures driving duct leaks can be extracted from the data taken during the Delta Q test for duct leakage is investigated. Curves of Delta Q vs. house pressure are generated for sets of cases where the supply and return leakage rates to/from outside are held constant while the leakage pressures are varied. It is found that the Delta Q curve takes on two qualitatively different shapes, one for leakage pressures within the range of house pressures used in the Delta Q test (i.e., -25 Pa to +25 Pa) and the other for leakage pressures well outside this range. These effects are seen in experimental data taken with leakage at known pressures. However, extracting the signal of the leakage pressure from the surrounding noise caused by random measurement variation is likely to be a difficult problem in many cases.

INTRODUCTION

The current state of the art in duct leakage testing can be summarized as follows. The fan pressurization (duct blower) test measures the leakage hole size (or one of its proxies, such as CFM25). To convert this into a leakage rate, one has to guess an effective pressure at a typical leakage site. The standard guess is one-half the pressure measured at the plenum, but this is less than satisfactory in that it can easily lead to errors of more than 50%.

The Delta Q test was developed by researchers at Lawrence Berkeley National Laboratory. In most cases, it probably is an improvement on fan pressurization, but one still has to guess supply and return leakage pressures to use as inputs to the Delta Q algorithm. While it is true that the Delta Q test is usually less sensitive to the leakage pressures than the fan pressurization test, the results can nevertheless still vary significantly depending on the choice of these pressures. (See Walker et al. 2001 or Andrews 2000 for a more complete description of the Delta Q test and derivation of its algorithm.)

Although the current version of the Delta Q test requires that the leakage pressures be guessed, there has been considerable interest in the question of whether and to what extent information on the leakage pressures can be extracted from the data taken in the Delta Q test. The hope that this might be possible is encouraged by the fact that the Delta Q algorithm produces ten equations in two unknowns (Q_{sleak} and Q_{rleak} , the supply and return leakage rates under normal operating conditions). The test is therefore “over-constrained” by eight equations. So why not just put in the supply and return leakage pressures as two additional unknowns? The test would still be over-constrained by six.

An attempt to do just that is certainly warranted. There are, however, at least two reasons why it might fail. The first problem could be mathematical difficulty. The leakage pressures appear in the equations in a way that is less amenable to solution by a straightforward least-squares fit than is the standard form of the test with the leakage pressures assumed and the leakage flow rates as the only unknowns. Of course, with a bit of cleverness, mathematical difficulties can usually be surmounted one way or another, particularly with the help of computers.

A second possible problem, however, might be more fundamental. It might turn out that the ten Delta Q values, which in addition to some measured pressures are the only items of information input into the test algorithm, don't embody much information about the leakage values. Or maybe they do provide this information under some conditions but not under others.

These considerations gave rise to the thought that it might be useful to perform a study of the impact of the leakage pressures on the Delta Q values obtained at the ten house pressures used in the test. Specifically, the question was asked, “What impact do the leakage pressures have on the shape of the Delta Q curve as a function of house pressure?” It is the purpose of this report to shed some light on this question.

A SIMPLE TEST CASE

From some previous analyses, a spreadsheet was available into which arbitrary sets of up to two leakage pressures and flow coefficients could be input on each side of the duct system, and the Delta Q values at the ten house pressures could be calculated. For the purposes of this study, it was assumed that measurement errors would be negligible. This was done so that variations in the shape of the Delta Q function could be seen as the leakage pressures were changed. It is a critical question, of course, whether these variations will be seen through the “noise” of the measurement errors that are unavoidable in the real world, but that is a follow-on question.

As a simple first case, let us consider a duct system in which there is no return leakage and in which the supply duct leaks to the outside at the rate of 100 cfm. Let the pressure at which this leakage occurs vary. Assuming a constant exponent in the pressure-flow equation, this means that the leakage flow coefficient will vary in the inverse direction. The 100 cfm of leakage could be produced by a small hole at a large pressure or a large hole at a small pressure.

Figure 1 shows the values of Delta Q, over the ten test house pressures, for leakage pressures of 60, 40, 20, and 10 Pa. It is worth looking at the shapes of these curves, for they contain elements that will be seen again and again.

Perhaps the first thing one notices is that the curves for 40 and 60 Pa leakage pressures are nearly identical. It is unlikely that experimental uncertainties in any real-world application of the Delta Q test would be small enough to distinguish between these two curves.

The second thing is that all the curves pass through 100 cfm at zero house pressure. In essence, the Delta Q at zero house pressure is identical to the first part of the nulling test, which measures the unbalanced leakage, i.e., the supply leakage minus the return leakage. (See Francisco and Palmiter 2001 for a complete description of this test.) In a real Delta Q test, even though the zero house pressure point is omitted for practical reasons, one can still usually determine which side of the duct has the greater amount of leakage, i.e., whether the leakage is supply- or return-dominant, by averaging the Delta Q values for +5 Pa and -5 Pa. If the average is positive, the system is supply-dominant and if it is negative it is return-dominant. There will, of course, be a gray area near zero where the leakage is more or less balanced.

The third thing is that, for negative house pressures, the low-leakage-pressure curves (10 and 20 Pa) are much different from the ones at higher leakage pressures. In the next section we'll see why this happens. Here, though, we can note a possible way of gleaning information about the leakage pressures from the shape of the Delta Q curve. Perhaps if the Delta Q curve is sigmoidal like the ones for the 40- and 60-Pa leakage pressures, one can say that the leakage pressure is “high,” whereas if it has a peak to the left of zero house pressure and then declines as the house pressure goes to the low end of its range (-25 Pa), this is evidence that the leakage pressure is “low.”

THE SHAPE OF THE DELTA Q CURVE

Delta Q is defined at any given house pressure P as the difference between the blower-door airflow rate needed to pressurize the house to P with the system fan on (Q_{on}) and the airflow needed to pressurize it to P with the system fan off (Q_{off}). If P is negative, then we are depressurizing the house. Q_{on} and Q_{off} are defined as positive for blower-door airflows into the house and negative for airflows out of the house. With these conventions in place, the Delta Q function, often written ΔQ , is given by:

$$\Delta Q = Q_{on} - Q_{off} \quad (1)$$

Q_{off} is the sum of two airflows: that needed to pressurize the house envelope to P and that needed to pressurize the duct system to P in its passive condition with the system fan off. Q_{on} is also the sum of two airflows: that needed to pressurize the house envelope to P and the net airflow into the duct system in its active mode with the system fan on. The latter quantity is in turn equal to the supply leakage to outside minus the return leakage from outside *at the condition in which the house currently is, namely pressurized to P*. This will, of course, not equal the unbalanced leakage under normal operation unless $P = 0$.

Because the airflow needed to pressurize the house envelope thus appears in both Q_{on} and Q_{off} , it cancels out in the equation for ΔQ . When making actual measurements, one cannot cancel out the envelope. One would like to, because envelope leakage adds to the uncertainty in the measurement of ΔQ even though it doesn't affect the expected value. But in understanding the behavior of ΔQ under various circumstances, it is permissible to ignore the envelope as long as one is not trying to include the effects of experimental uncertainty.

Let us therefore take Q_{off} to be just the airflow needed to pressurize the duct to P when the system fan is off, and Q_{on} to be the supply leakage to outside minus the return leakage from outside when the house is pressurized to P. Again, this will yield the correct answer for ΔQ because the thing we have ignored, the portion of the blower-door airflow needed to pressurize the envelope, is subtracted from itself and cancels out.

Consider now the simple situation from the previous section, namely a supply duct with 100 cfm leakage at a leakage pressure P_s . (Note for clarity: P_s , the leakage pressure, is a constant, while P, the house pressure, is a variable ranging from -25 Pa to $+25$ Pa.) If the exponent in the pressure-flow equation is n, then the leakage flow coefficient C_s of the duct is equal to $100/P_s^n$, and

$$Q_{off} = C_s \text{ sign}(P) |P|^{-n} \quad (2)$$

This is the familiar pressurization curve. It is shown in Figure 2.

The curve for Q_{on} has a similar shape but is shifted to the left by an amount equal to P_s . To see this, simply note that when the house is depressurized to $P = -P_s$, then the pressure difference across the leakage hole in the duct will be zero. (This assumes that the pressure difference

between the house and the duct remains constant, which is an approximation.) The curve for Q_{on} is shown in Figure 2 for the particular case $P_s = 20$ Pa.

ΔQ for any house pressure P is just the vertical distance between the curves for Q_{off} and Q_{on} . One can see that this difference attains a maximum somewhere between $P = -20$ and $P = 0$. In fact, the maximum occurs exactly halfway between, at $P = -10$. The ΔQ curve itself is also shown in Figure 2. Except for change of scale, it looks just like the corresponding curve in Figure 1.

Figure 3 shows the same set of curves as Figure 2, but now for the leakage pressure P_s equal to 60 Pa. The Q_{on} curve still has the same shape as the Q_{off} curve, but it is shifted to the left by 60 Pa rather than just 20. The effect of this is that the maximum value of ΔQ is not reached within the domain $-25 < P < 25$, which is why the ΔQ curve has the quite different shape that it does. The part that would droop down if we could look at house pressures closer to minus the leakage pressure is cut off. This is exactly the behavior seen in Figure 1 for the cases with leakage pressures equal to 40 or 60 Pa.

From this small study we can now form an idea of what it means for a leakage pressure to be “high” (with a sigmoidal ΔQ curve as in Figure 2 or the solid lines in Figure 1) or “low” (with a ΔQ curve that has a hump, as in Figure 3 or the dashed lines in Figure 1). A high value of the leakage pressure would be one that is well outside the -25 Pa to 25 Pa range within which data are taken, whereas a low value of leakage pressure would be one that is within this range. Leakage pressures just outside the range would likely be in a gray area where some downturn in the ΔQ curve might or might not be noticed, especially if experimental uncertainty contributes significant “noise” to the plot.

The above examples had supply leakage but not return. What happens if the reverse is true? The answer is very simple. If we have the plots for $Q_{sleak} = A$ and $Q_{rleak} = B$, with $A > B$, then the plots for $Q_{sleak} = B$ and $Q_{rleak} = A$ can be obtained from them via the transformation $\Delta Q \rightarrow -\Delta Q$ and $P \rightarrow -P$, i.e., rotating the graph by 180° . For example, Figure 4 shows the curves for $Q_{sleak} = 0$ and $Q_{rleak} = -100$ cfm. This is the same as Figure 2 rotated in the manner indicated.

LEAKAGE ON BOTH SIDES OF THE DUCT SYSTEM

So far, we’ve considered cases where leakage occurs on only one side of the duct system. Let us now generalize this to a case where supply leakage is dominant, but there is also a significant amount of return leakage. Specifically, consider the case where $Q_s = 100$ cfm and $Q_r = 50$ cfm, with the supply leakage pressure P_s and the return leakage pressure P_r as variable parameters.

There are more cases to study here than in the previous example, because combinations of leakage pressures have to be looked at. The results have therefore been split into two figures. Figure 5 shows the curves of ΔQ vs. house pressure for those cases where the return leakage pressure is “high”, i.e., 40 or 60 Pa. These curves have shapes very similar to those of their counterparts in Figure 1, the main difference being that the value of ΔQ at $P = 0$ is 50 rather than 100 Pa, reflecting the fact that the unbalanced leakage is now 50 Pa. Most of the difference between these curves and the ones in Figure 1 can be characterized as a downward shift of 50 Pa,

although there are some additional finer differences as well. From a “pattern recognition” standpoint, though, the curves are essentially the same as those for the supply-leakage-only case.

Figure 6 shows cases where the return leakage pressure is “low,” i.e., 10 or 20 Pa. The ΔQ curves for negative house pressures look very much like those of Figure 5. There’s a bit more structure for positive house pressures, the curves having minima at or near $P = 0.5 P_r$.

Perhaps when measurement error is included, the wiggles on the side with less leakage will be hard to decipher. Even then, it would still be a major step forward to be able to determine just the leakage pressure on the dominant side, particularly since the values of leakage returned by the ΔQ algorithm are usually more sensitive to the dominant-side leakage pressure than they are to the leakage pressure on the side with less leakage.

THE BALANCED-LEAKAGE CASE

If supply and return leakage are the same or nearly the same, both sides of the system will contribute equally to the shape of the ΔQ curve. Figures 7 and 8 show some of these cases. These can be perused to one’s heart’s content if the details are of interest, but they can be summarized very simply:

- The shape of the curve for negative house pressures is governed by the supply leakage pressure, while for positive house pressures it is governed by the return leakage pressure.
- For high leakage pressures (40 or 60 Pa) the curve is monotonic and sigmoidal, i.e., it has the sweeping S-shape, whereas for low leakage pressures (10 or 20 Pa) it has a peak.

These are the same characteristics that we saw in the cases where the leakage rates were unequal. It’s just that here they manifest themselves equally on both sides of the duct system.

REAL DATA

After reading the above, the most likely question on the reader’s mind is: Can one observe these effects in real data? The answer in many cases is Yes, but this is qualified by the effect of “noise” caused by experimental uncertainty.

The following examples are taken from data acquired in the BNL Thermal Distribution Test Facility. This is a full-scale residential-size duct system constructed in a high-bay facility surrounded by a high-mass concrete building envelope. It is described in more detail in a preliminary report (Andrews 2001) that also described other aspects of the Delta Q test results. It can be obtained by emailing the author (jwandrews@bnl.gov). Perhaps the one thing from this description to keep in mind is that the building envelope that was simulated was relatively “tight” as houses go, having a leakage rate at 25 Pa pressure, or CFM25, of ~900 cfm. Leakier envelopes will probably exhibit more random variation in the Delta Q curves, tighter envelopes less. Wind conditions also are expected to play a role. The effect of wind was noticeable during these tests, but because the register box is situated inside a large enclosure (which was, however, open to the outside during the tests) it is difficult to quantify wind effects in a way that could be transferred with confidence to actual houses.

Thirteen cases with independently measurable leakage were subjected to the Delta Q test, with eight repeats of the test for each leakage case. The Delta Q curves for several of these leakage cases are shown and discussed below.

Figure 9 shows a case where there is a large return leak at the plenum, whose measured pressure was -42 Pa during these tests. The unbalanced leakage is -300 cfm. Each line represents the Delta Q values for one of the eight tests at this condition. (The individual test points are not shown to eliminate clutter, but they are near, though not exactly at, the 5-Pa increments called for in the Delta Q protocol.) The general S-curve shape of the lines is evident, as is the inevitable variation caused by measurement errors. Although these curves are generally consistent with one another and with the actual experimental situation, there is enough variation among them to indicate that caution is in order in any attempt to interpret particular “wiggles” in any given curve.

Figure 10 shows a case where there was a return leak at low pressure, near the register. These curves seem quite consistent with one another, and they also agree in showing the minimum in the 5 to 15 Pa range. The measured static pressure at a point near this leak was -16 Pa, so this minimum is to be expected.

Figure 11 shows a supply leak in the form of an open branch directly off the main trunk duct. The measured supply plenum pressure during these tests was 14 Pa. The Delta Q curves show the positive unbalanced leakage and the expected maximum for negative house pressures. Again, though, although the group of curves is fairly consistent, the question remains concerning how much confidence one would place in the detailed wanderings of any one of them, if that were all the data one had.

Figure 12 shows a case similar to that of Figure 9, with a somewhat smaller leak at the return plenum. The unbalanced leakage is roughly half as great as in Figure 9, while the measured return-plenum pressure was -50 Pa (instead of the -42 Pa of Figure 9), the more negative value attributed to the reduced leakage nearby. There seems to have been somewhat more variation in this series of tests. In particular, the one that is highlighted by the dashed curve with displayed data points (asterisks) appears to show a definite minimum at -15 Pa. Another curve seems to show a maximum at -5 Pa, although this is the side with the smaller leakage rate, and so is not as significant. This just illustrates that although a large number of Delta Q curves may show the expected behavior, any given one may show significant deviation from the norm.

MULTIPLE LEAKAGE PRESSURES—A CAVEAT

This report has considered situations in which most or all of the supply leakage is concentrated at one single pressure and most or all of the return leakage is concentrated at another single pressure. Real duct systems usually have a variety of leaks at different pressures. There is some reason to believe that in many cases it makes sense to work with an “effective” leakage pressure that is, to a reasonable approximation, a weighted average of the actual leaks. This report, however, has not addressed the extent to which this assumption is valid.

ENHANCING THE LEAKAGE-PRESSURE SIGNAL

Modifications to the Delta Q test might enhance the leakage-pressure signal. Possibilities include taking points at more than ten house pressures or running the Delta Q test twice in succession. These measures would, of course, add to the time required to perform the test, though perhaps not by too much if an automated blower door is used.

It might be more time-efficient to expand the range of house pressures from -25 Pa through $+25$ Pa to, say, -40 Pa through $+40$ Pa, with an 8 Pa increment rather than the current 5 Pa. This might allow leakage-pressure information to be captured over a broader range of possible values for P_s and may also enhance the signal even for P_s values within the currently accessible range.

One concern in connection with this idea might be that systematic bias may increase as house pressures farther from zero are used in the Delta Q equations. That is a question for detailed study. However, if the actual house-to-duct pressures are used at each of the ten house pressures at which a ΔQ value is taken, instead of assuming a constant house-to-duct pressure, then expanding the range of house pressures might prove to be quite acceptable.

Finally, although this report has repeatedly cautioned against over-interpreting “wiggles” in a Delta Q curve in the face of unavoidable measurement errors, a strong countervailing positive factor should also be emphasized. Powerful filtering algorithms have been developed over the years whose purpose is precisely what is needed here – extracting signal from noise. This report makes no attempt to select or apply such techniques, but merely elucidates to some extent the kinds of signals that are to be looked for.

CONCLUSIONS

The objective of this study was to gain insights into the question of whether and to what extent useful values of effective leakage pressures in the supply and return ducts may be gleaned from information taken during a Delta Q test. The following conclusions were drawn:

- Any “signal” of the leakage pressure will be stronger and more evident on the side of the duct system that has the greater amount of leakage.
- The supply-side leakage pressure affects mainly the part of the Delta Q curve at negative house pressures. The return-side leakage pressure affects mainly the part of the Delta Q curve at positive house pressures.
- A leakage pressure within the range of the house pressures used in the Delta Q test tends to produce a Delta Q curve with a peak between -5 and -20 Pa (for supply leakage) or a trough between $+5$ and $+20$ Pa (for return leakage).
- Leakage pressures well outside this range tend to produce Delta Q curves that trail off to the horizontal for house pressures near -25 Pa (for supply leakage) or $+25$ Pa (for return leakage).
- For leakage pressures outside the -25 Pa to 25 Pa range, large variations in the leakage pressure produce small changes in the Delta Q curve.
- These effects have been observed in experimental data.
- However, variations caused by experimental error can impose a significant amount of noise on the Delta Q signal, making it more difficult to extract information on the leakage pressures.

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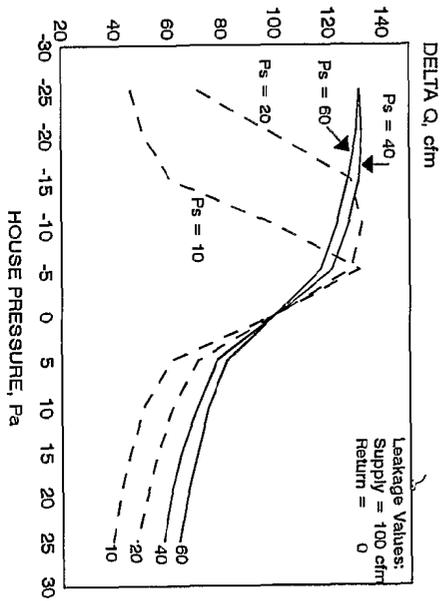


Figure 1. Delta Q Curves for Various Leakage Pressures

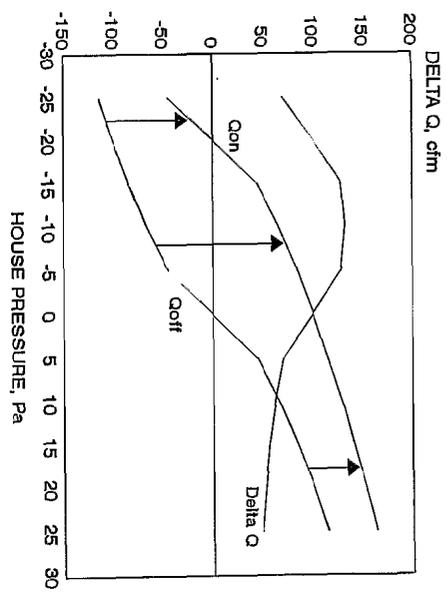


Figure 2. Construction of Delta Q Curve for Leakage at 20 Pascals

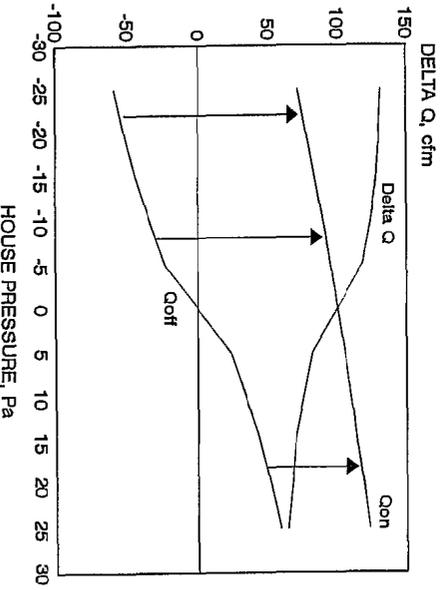


Figure 3. Construction of Delta Q Curve for Leakage at 60 Pascals

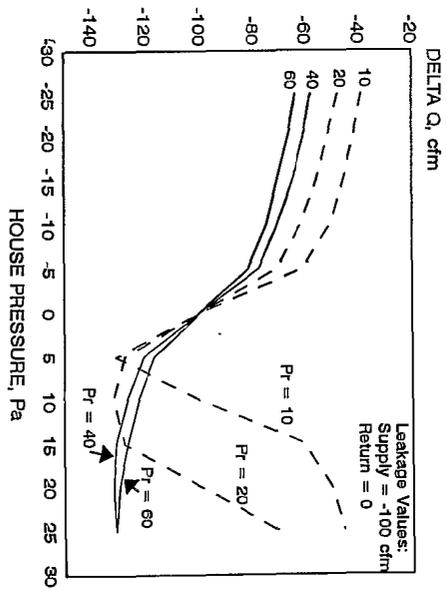


Figure 4. Delta Q Curve Shapes for Return-Side Leakage

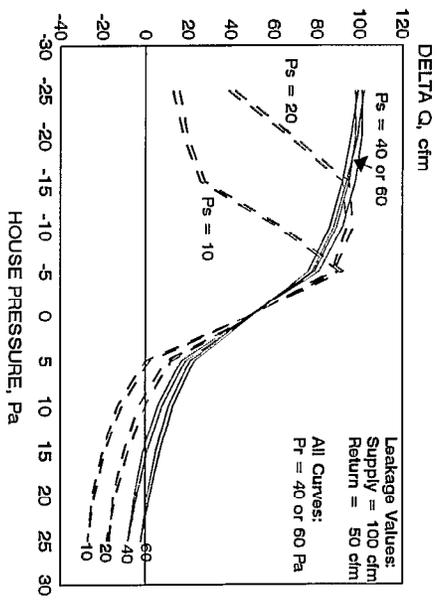


Figure 5. Delta Q Curves with Some Return Leakage -- High Return Leakage Pressure

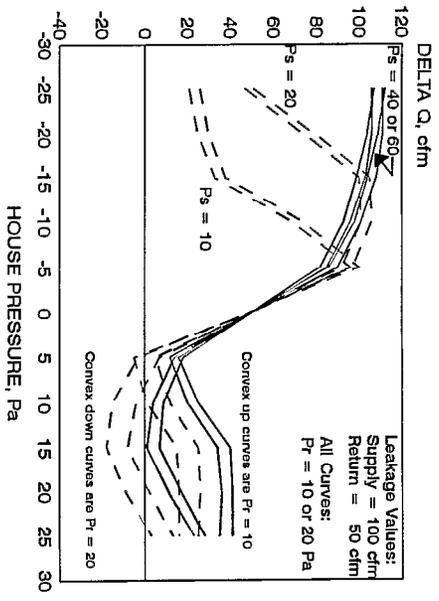


Figure 6. Delta Q Curves with Some Return Leakage -- Low Return Leakage Pressure

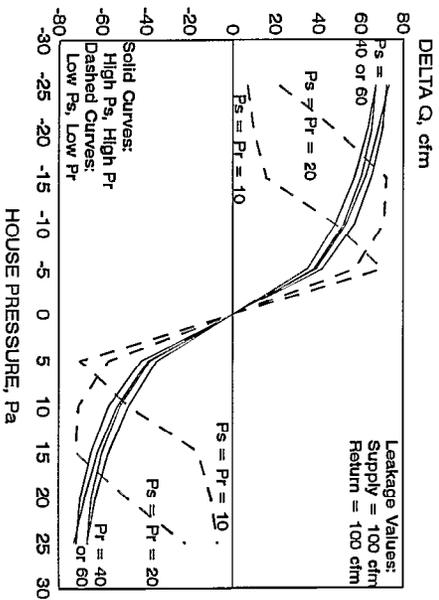


Figure 7. Delta Q Curves for Balanced Leakage Similar Leakage Pressures on Both Sides

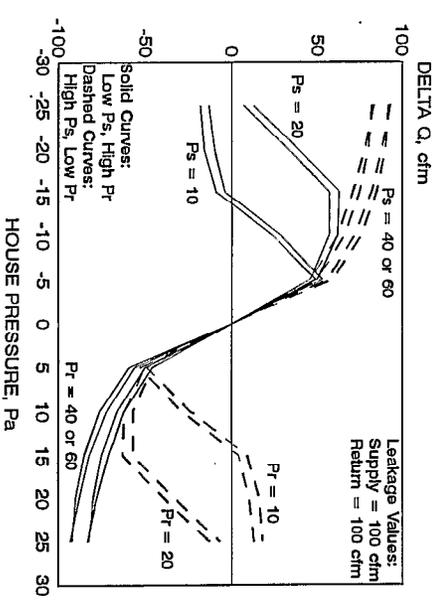


Figure 8. Delta Q Curves for Balanced Leakage Dissimilar Supply and Return Leakage Pressures

CASE C LEAKS SUPPLY: NONE RETURN: PLENUM (RING 1)

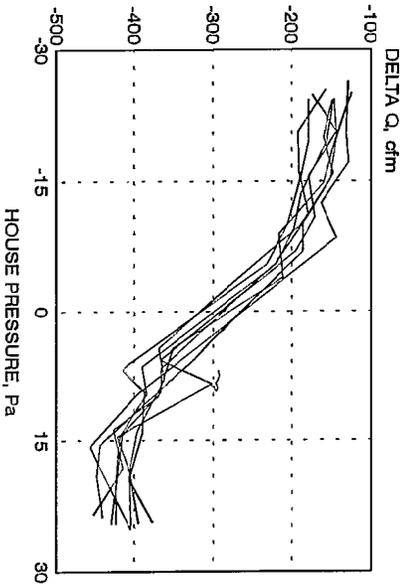


Figure 9. Measured Delta Q Curves -- Large Return Leak at Plenum

CASE K LEAKS SUPPLY: NONE RETURN: REGISTER (BAFFLE)

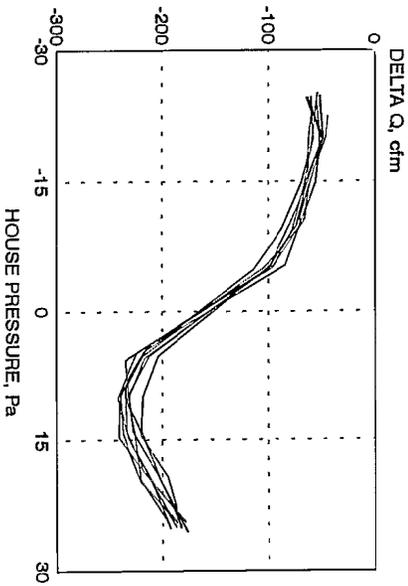


Figure 10. Measured Delta Q Curves -- Return Leak Near Register

CASE G LEAKS SUPPLY: OFF TRUNK RETURN: NONE

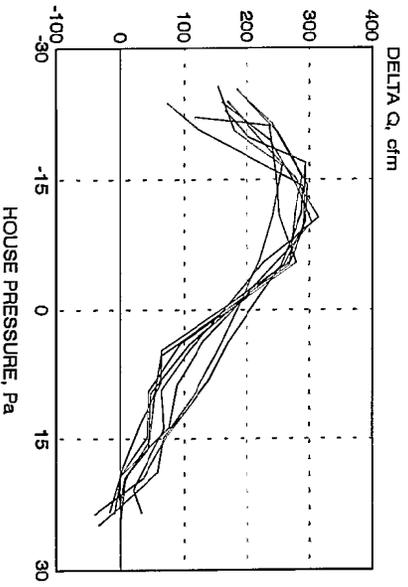


Figure 11. Measured Delta Q Curves -- Supply Leak off Trunk

CASE B LEAKS SUPPLY: NONE RETURN: PLENUM (RING 2)

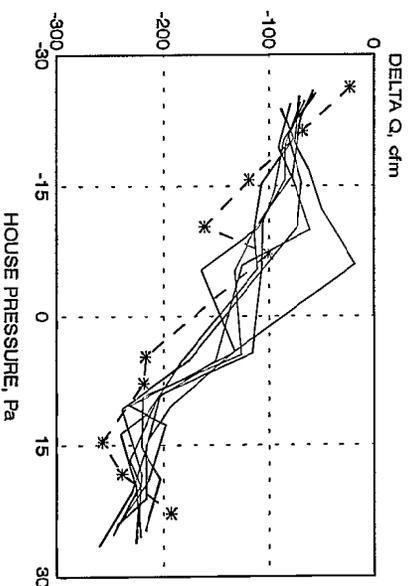


Figure 12. Measured Delta Q Curves -- Small Return Leak at Plenum