Development of a Field Procedure to Measure the Airtightness of Wall Construction Elements of Houses

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ABSTRACT

Whole-house tests were developed to compare the airflow resistance of several different materials used to seal the walls of a house at the outer surface. These airflow resistances were measured in field installations and include the effects of interactions with adjacent materials and assemblies. The materials tested were housewrap over fiberboard and foam sheathings, extruded polystyrene foam sheathing with the edges taped, extruded polystyrene sheathing with the edges untaped, and caulking and foaming the inside of the wall cavity. The comparisons were between different wall materials installed in sequence in the same house. In this way, any inherent differences in house construction that affected airtightness were accounted for.

It was found that, in rank order of airflow resistance:

1. The technique using housewrap over untaped extruded polystyrene foam sheathing had the highest flow resistance.

2. The next three methods each had about the same resistance to airflow, all approximately one-third less than that of the housewrap over foam sheathing. These were: housewrap over wood fiberboard sheathing, taped foam sheathing, and caulking and foaming the inside of the wall cavity.

The untaped foam sheathing by itself had very little flow resistance, approximately five times less than the previously ranked three. The drywall backed by kraft-faced batts had a flow resistance comparable to the best of the air-sealing techniques tested.

INTRODUCTION

This paper describes the results of whole-house tests developed to compare the airflow resistance of several different materials used to seal the walls of a house at the outer surface. These airflow resistances were measured in field installations and include the effects of interactions with adjacent materials and assemblies.

The materials tested were housewrap over fiberboard and foam sheathings, extruded polystyrene foam sheathing with the edges taped, extruded polystyrene sheathing with the edges untaped, and caulking and foaming the inside of the wall cavity. As part of the study, the airflow resistance of several other wall construction elements was also measured, including drywall, drywall with R-13 kraft-faced glass fiber batts, aluminum siding on plywood and fiberboard sheathing, and polyethylene sheeting (on the interior side of the drywall and covering the electrical outlets).

A blower door test is often used to measure and compare the effects of two wall materials on airtightness. The tests are done on similarly constructed houses set side by side but having different wall materials. The main disadvantage of this approach is that side-by-side houses are often not as similar as expected. Thus, one house, regardless of the material being evaluated, can be unintentionally built tighter than another.

The airtightness testing in this report was conducted on two side-by-side houses of nominally identical construction. However, the houses were not compared with each other. Rather, the same tests were carried out in each of the houses. In these tests, each wall material, once tested, was removed and replaced with another type for performance comparison. Thus, the comparisons were between different wall materials installed in the same house. In this way, any inherent differences in house construction that affected airtightness were accounted for.

By comparing the airtightness of the houses with each of the airtightness materials in place, the impact of their differing resistance to airflow through the wall cavities was determined. The following, in rank order of airflow resistance, was found:

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1. The technique using housewrap over untaped extruded polystyrene foam sheathing had the highest flow resistance.
2. The next three methods each had about the same resistance to airflow, all approximately one-third less than that of the housewrap over foam sheathing. These were:
    - housewrap over wood fiberboard sheathing,
    - taped foam sheathing, and
    - caulking and foaming the inside of the wall cavity.
3. The untaped foam sheathing by itself had very little flow resistance, approximately five times less than the previously ranked three.
4. The drywall backed by kraft-faced batts had a flow resistance comparable to the best of the air-sealing techniques tested.

EXPERIMENTAL PROCEDURE

The tests were performed by the authors in Granville, Ohio. The test houses, designated B and C, were 1361 ft^2 single-story wood-framed houses built in 1979 of conventional construction. They were nominally identical. The walls were constructed of 2-by-4 framing, plywood and wood fiberboard sheathing, and aluminum siding. The walls were 8 ft, 1¼ in. high from the bottom of the single bottom plate to the top of the double top plate. The plywood sheathing was placed next to the corners for bracing, and the fiberboard sheathing covered the remainder of the walls. The houses were heated with electric forced air furnaces. They differed slightly from occupied houses in that they did not have operating plumbing systems and that the basement access was through a door from the garage. Dummy plumbing vents were installed in the walls and extended through the roof, to simulate the air leakage effects of a plumbing system. Also, the drywall was screwed in place and sealed with duct tape instead of being nailed, taped, and finished with joint compound. This was done to facilitate removal and reinstallation, as the wall construction was changed during the test phases.

Airtightness of the houses was tested in both pressurization and depressurization using a blower door. The blower door manufacturer's calibration was used. The calibration was checked against a sharp-edged orifice and found to be within 3%. The repeatability of the measurements made in the field was checked by making frequent replicate measurements. The standard deviation was found to be about 1%. Little difference was found between the pressurization and depressurization results, so the average of them was used. Each pressurization and depressurization test was repeated at least twice, so each flow measurement was an average of at least 4 (and sometimes as many as 16) blower door tests.

The initial sequence of blower door testing of the houses was conducted with the exterior wall assembly as constructed in 1979: 2-by-4 framing, plywood and wood fiberboard sheathing, and aluminum siding. That sequence was as follows:

1. The houses were tested in an "empty cavity" mode first, having the drywall and cavity insulation removed. This was to determine the contribution of the sheathing and siding to the resistance of airflow.
2. Drywall was then installed over the empty cavity. The joints were taped with duct tape to simulate the airtightness of taped and plastered drywall. The connections to the ceiling and partition drywall were taped in the same way, and baseboard and trim were installed. Another blower door test was performed. This was to identify the contribution of the drywall to the resistance to airflow.
3. Polyethylene sheet was then installed over the entire interior surface of the walls, including the doors and windows. This was to determine the contribution of the exterior walls to the airflow into the house. The airtightness was again measured.
4. The "empty cavity" mode testing was then repeated.
5. R-13 kraft-faced cavity insulation was installed. The kraft paper was stapled to the sides of the studs, not to their outward-facing edges. Then the drywall with taped joints and the baseboards and trim were added. The airtightness was again measured.

This was followed by a series of tests in which each of the exterior surfaces of interest was installed in sequence. The airtightness of the house was measured again after each installation. Twenty-one tests of this type were performed in House C, and 14 tests in House B. The series of tests included housewrap over the plywood and wood fiberboard sheathing, the fiberboard sheathing replaced with extruded polystyrene foam sheathing with the joints and perimeter taped, the same foam sheathing with the joints and perimeter untaped, and housewrap over the same untaped foam sheathing.

All the components were installed by experienced contractors using their normal practices. The sheathing was installed resting on the outer edge of the subfloor. The roof trusses are raised trusses that have extra blocking at the ends where they rest on the walls. This allows room for the attic insulation. The top edges of the 8-foot sheathing boards were even with the middle of the upper board of the double top plate of the wall. Another foot of sheathing was then added above that to butt up against the top stringers of the roof truss and close the sides of the attic. At the bottom, the housewrap overlapped the concrete block foundation and was taped to it. At the top, the housewrap extended past the top of the wall and was taped to the 1-foot sheathing extensions.

One house was sealed with caulking and an expanding sprayed-foam sealant. These materials were installed in the exterior walls after the drywall and cavity insulation were removed. The sealants were applied along the perimeter of each cavity space where the framing met the sheathing, along the seams where framing members abutted, at electrical outlets, wherever wiring penetrated the framing, around doors and windows, and at the sole plate and top plate.

METHODOLOGY USED TO ANALYZE THE RESULTS

In the analysis that follows, the flows were calculated at 30 Pa because this pressure was in the middle of the range of pressures used in the blower door tests. When repeated tests were carried out at a single condition to evaluated accuracy, it was found that the variance of the flow at 30 Pa was less than that of other measures of the blower door test results. The airflow results could also be reported at 4 Pa, a pressure difference more closely associated with normal house conditions. However, the flows at 4 Pa would be extrapolations from the actual test pressures and are, therefore, not as accurate.

The results were analyzed by calculating the flow resistance of each of the wall components of interest. This approach was taken because the wall component being studied in each test was in series with other components that had already been tested. Because of the series arrangement, the flow resistances were additive. Therefore, the flow resistance increase caused by the installation of an individual component could be found by subtracting the flow resistance of the wall with the component absent from the flow resistance of the wall with the component present.

The total flow resistance of the wall was calculated as the inverse of the flow through the wall in each case. The flow resistances were then generalized by multiplying by the wall area and by the square root of the pressure used in the analysis, 30 Pa. Thus, the flow resistance of the walls is

$$R_w = P^{0.5}/(Q \cdot A)$$

where

P = the pressure at which the flows were calculated (Pa),

Q = the flow through the walls (m^3/s),

A = the area of the walls (m^2).

The flow resistance effect of a wall construction element is

$$R_e = R_w(2) - R_w(1)$$

where

$R_w(2)$ = the flow resistance of the walls after the wall construction element has been added, and

$R_w(1)$ = the flow resistance of the walls before the wall construction element has been added.

The units of the flow resistances calculated in this way are, therefore, $s \cdot Pa^{1/2}/m$. Thus, the results of the tests reported here can be compared to one another and to the results of other measurements made elsewhere. However, there are two limitations to the extension of these results.

One of these limitations is that wall airflow does not depend on the square root of pressure but on the pressure to some exponent between 0.5 and 1.0. Thus, the comparison will only be valid if the same nominal pressure (30 Pa) is used. The second limitation is more fundamental. These measurements were made in a field test. The results obtained depend to some extent on the nature of the houses tested. In the analysis, the walls were considered to be an airflow path in parallel with other flow paths through the ceiling, interior partitions, windows and doors, and basement. However, interactions probably occurred between these supposedly parallel flow paths. The measured resistances would, therefore, depend in part on these interactions.

For example, a significant leak through the plane of the drywall occurs at the junctions of the partitions with the outer walls. The drywall is not continuous there, and air can leak past the studs and into the interior partitions. It can then leak into the house through the switch and receptacle openings, under the drywall, etc. Similarly, air can leak from the attic around the top plate into the wall, bypassing the outer surface of the wall (the sheathing), but still flowing through the inner surface (the drywall).

The flow within the wall may also be far from the one-dimensional flows assumed for the analysis. The leaks in the outer surface and the inner surface will not be aligned, so that air will flow through the insulation parallel to the plane of the wall as well as normal to it.

Considering these complications, it would be more realistic to refer to "the incremental change in wall system flow resistance when the component is added." The term "flow resistance of the component" is used as an abbreviated way of expressing this meaning.

The effects of the wall components on the flow resistance of the outer walls of the house will depend on these three-dimensional flow patterns. This dependence is realistic. The same kinds of effects will be found in other houses. However, other houses will have slightly different structures, so the numerical values of the flow resistances that were measured in the present project will not apply precisely in those other houses.

Flow resistances of wall elements could be measured in the laboratory to overcome this difficulty. However, the leaks around the edges of these elements are a significant part of the total leakage as they are installed in real houses. Thus, the incremental resistances measured in a real house may be a better predictor of those to be expected in other houses than the resistances measured in a laboratory, in spite of the measurement problems caused by three-dimensional flow.

House C Analysis

The original intention was to consider the flow through the walls, when covered by the polyethylene vapor barrier on the inside surface, to be zero. However, when the measured results of the 21 tests carried out in House C were compared, it was found that several of the wall treatment configurations had lower flows through them than the one covered in polyethylene. This is because the polyethylene, installed on the inside of the house, could not prevent air from flowing into the exterior walls and then into the interior partitions and thence into the house. The exterior wall treatments, such as housewrap, caulking and sealing, and taped foam sheathing, could do so.

One approach to reach this zero airflow scenario was to assume that the tightest of the configurations measured was perfectly airtight. Then, by assuming that the airtightness of the balance of the house (other than the walls) stayed constant during all the changes that were made to the walls, the flow through the walls would be known for each test. The tightest of the configurations tested was the wall with vinyl siding, caulked and foamed, with R-13 kraft-faced glass fiber batts and drywall (Case 21).

However, the calculation of the resistance effects of the tighter wall components is very sensitive to this assumption. Since these tighter wall components are those of the greatest interest in this study, it was necessary to refine the assumption of the airtightness of the tightest wall. This was done by using the difference between Case 20 (drywall, R-13 KFB, caulk and foam, and vinyl siding) and Case 19 (empty cavity with caulk and foam and vinyl siding) to calculate the flow resistance effect of the drywall and R-13 KFB.

If the wall flow in Case 20 was assumed to be zero, then the flow resistance of the drywall and R-13 KFB would be infinite, an obviously incorrect result. Fortunately, the flow resistance of the drywall and R-13 KFB was measured in another pair of tests, Cases 8 and 9. This made it possible to adjust upward the assumed flow through the walls in Case 20 (the equivalent of adjusting downward the assumed flow through the other components of the house) until the two values of the calculated flow resistance of the drywall and R-13 KFB agreed. This result was achieved when 21.3% of the total flow through the house was assumed to pass through the walls in Case 20. Table A1 of Appendix A presents these results, arranged in order of flow resistance.

The previous measurement of the flow through the basement of House C was 330 cfm at 30 Pa, or 42.6% of the flow for Case 20. (The basement flow was determined by doing blower door tests with the basement windows and the door to the outside open and also with them closed. The basement pressure was measured during each of these tests. These results provided the equivalent of a blower door test on the basement ceiling.) The previous measurement of the flow through the windows and doors was 102 cfm (or 13.2% of the flow for Case 20). Of the remaining area, 49% is ceiling and 51% is wall. If the ceiling and walls were equally leaky per unit area, 22.1% of the flow would be expected to pass through the walls, very close to the 21.3% (165 cfm at 30 Pa) that was estimated by the method described above. However, the airtightness measurements of the wall components indicate that the walls should be tighter than the ceiling, which consists only of drywall and glass fiber insulation. If the ceiling had the same resistance as the drywall and R-13 KFB of the walls, then about 17% of the total flow (132 cfm at 30 Pa) would go through the walls in Case 21. This seems like a realistic estimate, since the kraft paper facing would make the walls tighter, but the electrical wiring and electrical outlets would make them leakier.

To investigate the sensitivity of the results to the assumption made about the flow through the wall in Case 20, two further analyses were done. In the first, the flow through the walls in Case 20 was assumed to be 17% of the total flow (132 cfm at 30 Pa), as estimated above. In the second, the reduction from the original estimate of 21.3% (165 cfm at 30 Pa) was doubled, so that the wall flow was 12.8% of the total (99 cfm at 30 Pa). These results are presented in Tables A2 and A3 of Appendix A.

House B Analysis

The method of estimating the airflow through the balance of the house (other than the walls) used in the analysis of the House C results could not be used in House B. House B was modified between Tests 11 and 12 of the test sequence in ways that would change its airtightness. In particular, two door frames were replaced due to problems with the locks, and excavation was carried out near the foundation in connection with the installation of a telephone line. Thus, it could not be assumed that the airtightness of the remainder of the house stayed constant during the sequence of tests (which assumption was the basis of the House C analysis described above).

As an alternative means to estimate the airflow through the balance of the house, it was assumed that the tightest wall configuration that was tested in both House B and House C had the same airflow in each house. This was the empty cavity with drywall and polyethylene. This assumption was made for each of the three airflow rates that were studied for House C. That is, the assumed airflow rate through the balance of House B was adjusted so that the airflow through the empty cavity with drywall and polyethylene in House B was the same as it had been in each of the three cases that had been analyzed for house C. The airflow resistance of each of the other wall types studied was then evaluated for each of the three resulting airflow rates through the balance of the house.

This methodology was applied to Tests 1 through 11 in House B, the tests that were made before the modifications to the house occurred. The results are presented in Tables A4, A5, and A6 of Appendix A.

A similar methodology could not be applied to Tests 12 through 14, which were performed after the modifications to the house had occurred. No method could be found that could normalize these results to make them comparable with the other results of House B or with those of House C. Therefore, these results were not analyzed further.

DISCUSSION OF RESULTS

Accuracy of Results

A first observation is that the calculated flow resistance effects of wall elements found in Appendix A are very sensitive to small differences in measured flow. To illustrate this point, consider the measurements of the airtightness of the walls with housewrap (Case 8 in House C) and that of the taped foam sheathing (Case 13 in House C). The airflows through the whole house in these two cases are only 1% different, 848 cfm and 840 cfm, respectively. However, this 1% change in airflow caused about a 10% difference between the calculated flow resistances of the housewrap and the taped foam sheathing. This 1% difference is equal to the standard deviation of a series of blower door measurements on an unchanged building. This difference is also less than the variation that was measured on the same wall element before and after a set of test series: first, untaped foam sheathing, then taping the foam sheathing, then untaping the same foam sheathing and applying housewrap, then finally back to the original condition of untaped foam sheathing. Thus, the error in the flow resistances caused by measurement error and by unintentional changes to the other parts of the house from test to test is probably greater than the 10% difference between the calculated flow resistances of the two wall elements, and the resistance measurements should not be considered to be significantly different.

Three tables of flow resistances were prepared for each of the two houses studied. These tables are presented in Appendix A. The results in these tables differ because of the different assumptions made as described above. An examination of the three tables of flow resistances, prepared from the measurements made in House C (Tables A1, A2, and A3) shows a slight change in the rank order of the resistances of the materials. However, when the uncertainty in the results, as discussed in the previous paragraph, is taken into consideration, it becomes clear that these changes in rank order have no real significance. The materials that interchange in rank order should actually be regarded as having essentially the same resistance to airflow. When the three tables of flow resistances produced from the data measured in House B (Tables A4, A5, and A6) are compared, a similar conclusion is reached. Thus, it is not important which of the three tables is considered in further discussion.

Since it is not important which of the three tables is considered, Tables A2 and A5 from Appendix A are reproduced here in simplified form as Table 1 and Table 2, with the results appropriately averaged (where there are two values for the same material) and rounded off.

The results were rounded off to the nearest 500 $s \cdot Pa^{0.5}/m$. This precision was chosen because it made the order of the results independent of the assumption that was made about the percentage of the total flow that went through the walls. Thus, it is a reasonable estimate of the relative accuracy. It is unlikely that a wall component shown as having a higher flow resistance than another in Tables 1 or 2 actually had a lower flow resistance.

The absolute accuracy can be estimated by considering three variations in the results obtained. One is the variation in results when the same material was tested more than once. The second is the variation caused by assuming different percentages of the total leakage are in the walls. The third is the variation in the results from House B to House C.

Two pairs of results are available for comparison in House C: kraft-faced batts with drywall and aluminum siding with sheathing. In Table A2 in Appendix A, the percentage difference of the former readings from the average is 7% and of the latter, 0.6%. In House B, only the aluminum siding with sheathing is available for comparison. The standard deviation of the three readings is 6%. These figures indicate that the error due to measurement inaccuracies and changes to the house between tests is small.

The deviations caused by the uncertainty about the percentage of the total flow that goes through the walls are much greater. In House C, the variation in the calculated flow resistance caused by the assumption made about the flow through the walls ranges from about 7% for aluminum siding with sheathing up to a factor of almost 2 for the kraft-faced batts with drywall. This means that the results obtained here cannot be treated as absolute values. However, the estimation of the percentage flow through the walls has little effect on the relative flow resistance of the various wall components, so the results are useful for comparing the airtightness of the components.

A comparison of the resistances of the wall components in House B and House C is also useful for assessing the accuracy of the results. The deviations of the resistances in TableA2 (House C) from those in Table A5 (House B) for the same materials range from 1% to 27%. Both of these tables are based on the same value, (220 cfm at 30 Pa) for the airflow through the walls with the polyethylene seal in place. The deviation between the results in these two tables is due in part to the differences in construction details from house to house and in part to experimental error.

A significant uncertainty has been introduced into the results obtained by the leakage past the polyethylene sheet that was placed on the insides of the walls. The estimation method described above in the "House C Analysis" section allowed the relative ranking of the flow resistance effects of the various wall construction elements to be determined with accuracy. However, there is a great deal of uncertainty in the absolute values of the flow resistances measured.

Discussion

As Table 1 shows, the three main airtightening techniques tested (taped foam sheathing, caulking and foaming the wall from inside, and housewrap over fiberboard sheathing) yield essentially the same results in the House C tests. Housewrap over untaped foam sheathing has a resistance about 50% higher. However, to keep this difference in perspective, it should be noted that it caused a reduction in total airflow through the house of only about 4% compared to the other sealing methods.

Polyethylene applied to the inside of the drywall has an airtightness greater than the first three methods mentioned and less than housewrap over untaped foam sheathing. However, this application of polyethylene is not comparable to the use of the same material in real construction, since it is on the wrong side of the drywall, it does not isolate the ends of the interior partitions from the wall, and it covers the electrical outlets.

It is interesting to note that, in the House C tests, the drywall with R-13 kraft-faced batts has a flow resistance that is substantially greater, by two-thirds, than the three methods of sealing the wall at the outer surface.

One curious result that can be seen in Table 1 is the range of flow resistances shown by some materials. For example, drywall ranges from 2600 s·Pa$^{1/2}$/m down to 1400 s·Pa$^{1/2}$/m. R-13 kraft-faced batts range from 2000 s·Pa$^{1/2}$/m down to 300 s·Pa$^{1/2}$/m. At first glance, this might seem to raise a question about the accuracy of the test procedure or the calculations. However, a comparison of the high-resistance cases and the low-resistance cases shows that the former involved installation of the material to be tested in a wall of normal configuration. The latter, on the other hand, involved installation of the material to be tested in a wall in which the normal adjacent material was missing. For example, in Test 11, which produced the resistance of 300 s·Pa$^{1/2}$/m, the R-13 kraft-faced batts were installed in a wall without siding or drywall.

TABLE 1
Flow Resistance Effects of Wall Elements - House C

(Based on Table A2, Appendix A)		
Material	**Test Comparison**	**Flow Resistance s·Pa$^{0.5}$/m**
R-13 KFB+drywall	20 vs. 19 & 9 vs. 8	5500
Housewrap & untaped foam	14 vs. 7	5000
Polyethylene	3 vs. 2	4000
Taped foam sheathing	13 vs. 7	3500
Caulk and foam	19 vs. 18	3000
Housewrap (over fiberboard)	7 vs. 8	3000
Drywall	15 vs. 11 & 12 vs. 11	2500
R-13 KFB	6 vs. 2	2000
Vinyl siding	17 vs. 15	2000
Alum. siding and sheathing	4 & 1	1500
Drywall*	2 vs. 1	1500
Untaped foam sheathing	10 vs. 5	500
Aluminum siding	6 vs. 7	500
R-13 KFB*	11 vs. 10	500

* Note that in the marked cases the wall component measured was not in its usual position in the wall, so that the results are not comparable with other measurements for the same component.

To understand how this nontypical installation could produce a different flow resistance measurement, consider two sheets of plywood. One sheet has a round orifice 1 foot in radius cut into the middle of the top half, and the other has a round orifice 1 foot in radius cut into the middle of the bottom half. If the airflow resistance of each sheet is measured separately, they will be very low, about 5 s·Pa$^{1/2}$/m. If the two sheets are fastened together face to face so that the holes are not aligned, the flow resistance will be far higher. This is because the flow resistance being measured is no longer that of the plywood sheets. It is the flow resistance through the thin space between the two plywood sheets from the hole in the top half of one sheet down to the hole in the bottom half of the other sheet.

The same phenomenon occurs when R-13 kraft-faced batts are installed in a wall next to drywall. The leaks in the kraft paper will not be aligned with those in the drywall. Also, the leaks in the sheathing will not be aligned with the leaks in the drywall. In this case, the leaking air must flow up or down along a long path through the insulation instead of directly across the wall. In many cases, it will also have to leak through a small crack from one stud space to another. Thus, the flow resistance of a wall can not usually be predicted by adding up the flow resistances of the individual elements, unless these flow resistances are measured with the elements in their normal position in the wall.

Another complication could occur if the kraft paper were pulled away from the drywall when the house was pressurized and pressed against it when the house was depressurized. The path between the kraft paper and the drywall would be opened up in the former case, reducing the flow resistance of the wall. However, that was not the case in the present study. Pressurization and depressurization measurements were carried out in every test, and there were no significant differences between them.

This observation does not diminish the value of the measurements of the flow resistance effect that were made in the present study. This is because the flow resistance effects of the wall elements of interest were measured by installing the wall elements in complete walls, as they would be applied in the field. The only missing wall element in these tests was the siding. Given the relatively modest effect of removing the siding in Test 7, it is unlikely that the effect of this lack of siding on the airtightnesses of the other wall components would be significant.

Although no test measured the flow resistance effect of fiberboard sheathing directly, two tests, 7 and 12, were the same except that the former was done with untaped fiberboard sheathing in place and the latter with untaped foam sheathing. The flows in the two tests differ by only 20 cfm, or 2% of the total. This difference is not significant, so the flow resistance effects of the two sheathing materials are the same.

An examination of the results of the House B tests, in Table 2, shows that the airflow resistances of the housewrap, R-13 kraft-faced batts, drywall over an empty cavity, siding and sheathing, aluminum siding, and drywall in a conventional wall, are the same as in House C within the range of the expected experimental error. The airflow resistance of the polyethylene over drywall is one-third lower in House B than in House C. This difference may be due to differences in the care taken in the installation and taping of the polyethylene sheet.

These results are, of course, valid only for the two houses tested. It is likely that the contribution of wall construction elements to the airtightness of walls will vary, depending on the details of construction of the walls and their connections to the rest of the house. In fact, it is this dependence that makes the type of testing reported here useful. Further tests in other houses will be necessary to provide generally meaningful results.

TABLE 2
Flow Resistance Effects of Wall Elements - House B

(Based on Table A5, Appendix A)

Material	Test Comparison	Flow Resistance $s \cdot Pa^{0.5}/m$
Drywall	7 vs. 8	3000
Polyethylene	3 vs. 2	2500
Housewrap (over fiberboard)	10 vs. 9	2500
Drywall*	2 vs. 1	2000*
Alum. siding and sheathing	1, 4 & 6	1500
Aluminum siding	9 vs. 8 & 11 vs. 6	500
R-13 KFB*	6 vs. 7	500*

* Note that in the marked cases the wall component measured was not in its usual position in the wall, so that the results are not comparable with other measurements for the same component.

The main source of uncertainty in the results reported here was the uncertainty in the flow through the rest of the house. This was caused by the failure of the interior polyethylene sheet to be completely airtight in the test designed to measure that flow. Several steps should be taken to avoid this problem in future tests of this type. One is to do the "zero wall leakage" test with the polyethylene cover over the wall that is expected to be the tightest. The second is to cover the outside of the wall as well as the inside with polyethylene sheet, well sealed at joints as well as around the edges. A third improvement would be to seal the junctions of the interior partitions with the walls. However, this may be difficult and expensive to do in most cases. If this step is taken, it will be necessary to remove the seal afterwards (or do this test last) to avoid affecting the results of the tests of wall construction element resistance.

CONCLUSIONS

It was found that:

1. The technique using housewrap over untaped extruded polystyrene foam sheathing had the highest flow resistance effect of the air-sealing techniques tested.
2. The next three methods each added about the same resistance to airflow, all approximately 40% less than that of the housewrap over foam sheathing. These were
   - housewrap over wood fiberboard sheathing,
   - taped foam sheathing, and
   - caulking and foaming the inside of the wall cavity.
3. The untaped foam sheathing by itself added very little flow resistance, approximately five times less than the previously ranked three.
4. The drywall backed by kraft-faced batts added a flow resistance comparable to the best of the air-sealing techniques tested.

The technique used in this project shows promise as a method of determining the contributions of the components of walls to their airflow resistance. However, in future tests, the walls must be sealed better during the test designed to measure the airflow through the other parts of the house.

APPENDIX A

Tables of Flow Resistance

TABLE A1a
House C - Flows through Wall Elements

Flow through the walls in Case 20 = 21.3% of the total flow.			
Case Number	Case Name	30 Pa Flow [cfm]	Wall Flow [cfm]
1	Empty cavity	1744	1134
2	Empty cavity with drywall	1197	587
3	Empty cavity with drywall and poly	863	253
4	Empty cavity	1729	1119
5	Average of empty cavity cases	1737	1127
6	R-13 KFB with drywall	960	350
7	R-13 KFB with drywall/no siding	992	382
8	R-13 KFB with drywall and housewrap/no siding	848	238
9	Empty cavity with housewrap/no siding	1294	684
10	Empty cavity with foam sheathing/no siding	1427	817
11	R-13 KFB & foam sheathing with no drywall/no siding	1334	724
12	R-13 KFB & foam sheathing with drywall, no siding	1012	402
13	R-13 KFB & taped foam sheathing with drywall, no siding	840	230
14	R-13 KFB with drywall + foam sh. & housewrap/no siding	807	197
15	R-13 KFB with drywall and untaped foam sheathing/no siding	919	309
16	R-13 KFB as above, taped foam sheathing w/paper flap	893	283
17	R-13 KFB with vinyl siding, drywall & untaped sheathing	849	239
18	Empty cavity with vinyl siding	1234	624
19	Empty cavity with caulk and foam and vinyl siding	911	301
20	R-13 KFB drywall, caulk and foam, vinyl siding	775	165

TABLE A1b
House C - Flow Resistance of Wall Elements

Flow through the walls in Case 20 = 21.3% of the total flow.		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
R-13 KFB+drywall	9 vs. 8	4190
R-13 KFB+drywall	20 vs. 19	4188
Housewrap & foam	14 vs. 7	3760
Poly	3 vs. 2	3440
Drywall	15 vs. 11	2837
Taped foam sheathing	13 vs. 7	2646
Caulk and foam	19 vs. 18	2630
Housewrap	7 vs. 8	2422
R-13 KFB	6 vs. 2	1764
Drywall	12 v.s 11	1692
Vinyl siding	17 vs. 15	1450
Alum. siding and sheathing	4	1367
Alum. siding and sheathing	(4 + 1)/2	1358
Alum. siding and sheathing	1	1349
Drywall	2 vs. 1	1257
Untaped foam sheath	10 vs. 5	515
Aluminum siding	6 vs. 7	366
R-13 KFB	11 vs. 10	240

TABLE A2a
House C - Flows through Wall Elements

Flow through the walls in Case 20 = 17% of the total flow			
Case Number	**Case Name**	**30 Pa Flow [cfm]**	**Wall Flow [cfm]**
1	Empty cavity	1744	1101
2	Empty cavity with drywall	1197	554
3	Empty cavity with drywall and poly	863	220
4	Empty cavity	1729	1086
5	Average of empty cavity cases	1737	1094
6	R-13 KFB with drywall	960	317
7	R-13 KFB with drywall/no siding	992	349
8	R-13 KFB with drywall and housewrap/no siding	848	205
9	Empty cavity with housewrap/no siding	1294	651
10	Empty cavity with foam sheathing/no siding	1427	784
11	R-13 KFB & foam sheathing with no drywall/no siding	1334	691
12	R-13 KFB & foam sheathing with drywall, no siding	1012	369
13	R-13 KFB & taped foam sheathing with drywall, no siding	840	197
14	R-13 KFB with drywall + foam sh. & housewrap/no siding	807	164
15	R-13 KFB with drywall and untaped foam sheathing/no siding	919	276
16	R-13 KFB as above, taped foam sheathing w/paper flap	893	250
17	R-13 KFB with vinyl siding, drywall & untaped sheathing	849	206
18	Empty cavity with vinyl siding	1234	591
19	Empty cavity with caulk and foam and vinyl siding	911	268
20	R-13 KFB drywall, caulk and foam, vinyl siding	775	132

TABLE A2b
House C - Flow Resistance of Wall Elements

Flow through the walls in Case 20 = 17% of the total flow.		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
R-13 KFB+drywall	20 vs. 19	5880
R-13 KFB+drywall	9 vs. 8	5111
Housewrap & foam	14 vs. 7	4944
Poly	3 vs. 2	4191
Taped foam sheathing	13 vs. 7	3381
Drywall	15 vs. 11	3328
Caulk and foam	19 vs. 18	3119
Housewrap	7 vs. 8	3078
R-13 KFB	6 vs. 2	2064
Drywall	12 vs. 11	1931
Vinyl siding	17 vs. 15	1883
Alum. siding and sheathing	4	1408
Alum. siding and sheathing	(4 + 1)/2	1399
Alum. siding and sheathing	1	1389
Drywall	2 vs. 1	1372
Untaped foam sheath	10 vs. 5	553
Aluminum siding	6 vs. 7	442
R-13 KFB	11 vs. 10	263

TABLE A3a
House C - Flows through Wall Elements

Flow through the walls in Case 20 = 12.8% of the total flow.			
Case Number	**Case Name**	**30 Pa Flow [cfm]**	**Wall Flow [cfm]**
1	Empty cavity	1744	1068
2	Empty cavity with drywall	1197	521
3	Empty cavity with drywall and poly	863	187
4	Empty cavity	1729	1053
5	Average of empty cavity cases	1737	1061
6	R-13 KFB with drywall	960	284
7	R-13 KFB with drywall/no siding	992	316
8	R-13 KFB with drywall and housewrap/no siding	848	172
9	Empty cavity with housewrap/no siding	1294	618
10	Empty cavity with foam sheathing/no siding	1427	751
11	R-13 KFB & foam sheathing with no drywall/no siding	1334	658
12	R-13 KFB & foam sheathing with drywall, no siding	1012	336
13	R-13 KFB & taped foam sheathing with drywall, no siding	840	164
14	R-13 KFB with drywall + foam sh. & housewrap/no siding	807	131
15	R-13 KFB with drywall and untaped foam sheathing/no siding	919	243
16	R-13 KFB as above, taped foam sheathing w/paper flap	893	217
17	R-13 KFB with vinyl siding, drywall & untaped sheathing	849	173
18	Empty cavity with vinyl siding	1234	558
19	Empty cavity with caulk and foam and vinyl siding	911	235
20	R-13 KFB drywall, caulk and foam, vinyl siding	775	99

TABLE A3b
House C - Flow Resistance Effects of Wall Elements

Flow through the walls in Case 20 = 12.8% of the total flow.		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
R-13 KFB+drywall	20 vs. 19	8941
Housewrap & foam	14 vs. 7	6835
R-13 KFB+drywall	9 vs. 8	6417
Poly	3 vs. 2	5243
Taped foam sheathing	13 vs. 7	4486
Housewrap	7 vs. 8	4052
Drywall	15 vs. 11	3970
Caulk and foam	19 vs. 18	3767
Vinyl siding	17 vs. 15	2547
R-13 KFB	6 vs. 2	2450
Drywall	12 vs. 11	2228
Drywall	2 vs. 1	1504
Alum. siding and sheathing	4	1452
Alum. siding and sheathing	(4 + 1)/2	1442
Alum. siding and sheathing	1	1432
Untaped foam sheath	10 vs. 5	595
Aluminum siding	6 vs. 7	545
R-13 KFB	11 vs. 10	288

TABLE A4a
House B - Flow through Wall Elements

Poly flow matched to poly flow for Table A-1a			
Case Number	**Case Name**	**30 Pa Flow [cfm]**	**Wall Flow [cfm]**
1	Empty cavity	1524	964
2	Empty cavity with drywall	1013	453
3	Empty cavity with drywall and poly	813	253
4	Empty cavity - May 31, 1996	1584	1024
5	Average of May empty cavity cases	1554	994
6	Empty cavity - June 17, 1996	1441	881
7	R-13 KFB with no drywall	1311	751
8	R-13 KFB with drywall	879	319
9	R-13 KFB with drywall, no siding.	955	395
10	R-13 KFB with drywall and housewrap, no siding.	797	237
11	Empty cavity with no siding	1472	912

TABLE A4b
House B - Flow Resistance of Wall Elements

Poly flow matched to poly flow for Table A-1a		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
Drywall	7 vs. 8	2758
Poly	3 vs. 2	2669
Housewrap	10 vs. 9	2581
Drywall	2 vs. 1	1790
Alum. siding and sheathing	6	1736
Alum. siding and sheathing	1	1587
Alum. siding and sheathing	(4 + 1)/2	1540
Alum. siding and sheathing	4	1494
Aluminum siding	9 vs. 8	922
R-13 KFB	6 vs. 7	301
Aluminum siding	11 vs. 6	59

TABLE A5a
House B - Flows through Wall Elements

Poly flow matched to poly flow for Table A-2a			
Case Number	**Case Name**	**30 Pa Flow [cfm]**	**Wall Flow [cfm]**
1	Empty cavity	1524	931
2	Empty cavity with drywall	1013	420
3	Empty cavity with drywall and poly	813	220
4	Empty cavity - May 31, 1996	1584	991
5	Average of May empty cavity cases	1554	961
6	Empty cavity - June 17, 1996	1441	848
7	R-13 KFB with no drywall	1311	718
8	R-13 KFB with drywall	879	286
9	R-13 KFB with drywall, no siding.	955	362
10	R-13 KFB with drywall and housewrap, no siding.	797	204
11	Empty cavity with no siding	1472	879

TABLE A5b
House B - Flow Resistance of Wall Elements

Poly flow matched to poly flow for Table A-2a		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
Poly	3 vs. 2	3311
Housewrap	10 vs. 9	3272
Drywall	7 vs. 8	3218
Drywall	2 vs. 1	1999
Alum. siding and sheathing	6	1804
Alum. siding and sheathing	1	1643
Alum. siding and sheathing	(4 + 1)/2	1593
Alum. siding and sheathing	4	1543
Aluminum siding	9 vs. 8	1123
R-13 KFB	6 vs. 7	327
Aluminum siding	11 vs. 6	64

TABLE A6a
House B - Flow through Wall Elements

Poly flow matched to poly flow for Table A-3a			
Case Number	**Case Name**	**30 Pa Flow [cfm]**	**Wall Flow [cfm]**
1	Empty cavity	1524	898
2	Empty cavity with drywall	1013	387
3	Empty cavity with drywall and poly	813	187
4	Empty cavity - May 31, 1996	1584	958
5	Average of May empty cavity cases	1554	928
6	Empty cavity - June 17, 1996	1441	815
7	R-13 KFB with no drywall	1311	685
8	R-13 KFB with drywall	879	253
9	R-13 KFB with drywall, no siding.	955	329
10	R-13 KFB with drywall and housewrap, no siding.	797	171
11	Empty cavity with no siding	1472	846

TABLE A6b
House B - Flow Resistance of Wall Elements

Poly flow matched to poly flow for Table A-3a		
Material	**Test Comparison**	**Flow Resistance, s-Pa^0.5/m**
Housewrap	10 vs. 9	4295
Poly	3 vs. 2	4227
Drywall	7 vs. 8	3813
Drywall	2 vs. 1	2249
Alum. siding and sheathing	6	1877
Alum. siding and sheathing	1	1703
Alum. siding and sheathing	(4 + 1)/2	1650
Alum. siding and sheathing	4	1597
Aluminum siding	9 vs. 8	1396
R-13 KFB	6 vs. 7	356
Aluminum siding	11 vs. 6	69