Ian Sacs spent his summer fellowship with the Building Technologies Center at ORNL where he worked alongside researcher Mark Ternes on several existing projects. His responsibilities included the design and population of a relational database to organize previously collected research data, as well as participating in several field investigations such as the one described in this journal. Ian says his ten-week internship at the laboratory was an intense learning experience of advanced technologies, interesting research, and respected scientists. He is currently a graduate student in the Civil Engineering Department at University of Tennessee. Ian's future plans are to finish graduate school, volunteer for the Peace Corps, and then pay back his student loans!

Mark Ternes is the Team Leader for Residential Building Research within the Buildings Technology Center at the Oak Ridge National Laboratory. He currently serves as the Residential Sector Market Manager for the U.S. Department of Energy's Rebuild America Program. His expertise includes developing techniques to improve the performance of buildings and energy systems, field testing the performance of energy measures in heating and cooling climates, and developing materials and methods to enable the adoption of best practices by designers, contractors, and operators. He has managed major residential research and development projects for the U.S. Department of Energy, as well as the Army and Air Force. Mark has an MSME from the University of Tennessee and a BSME from the University of Florida.

FIELD VALIDATION OF ICF RESIDENTIAL BUILDING AIR-TIGHTNESS

Ian Sacs and Mark P. Ternes

ABSTRACT

Recent advances in home construction methods have made considerable progress in addressing energy savings issues. Certain methods are potentially capable of tightening the building envelope, consequently reducing air leakage and minimizing heating and air conditioning related energy losses. Insulated concrete form (ICF) is an economically viable alternative to traditional wood-frame construction. Two homes, one of wood-frame, the other of ICF construction, were studied. Standard air leakage testing procedures were used to compare air tightness characteristics achieved by the two construction types. The ICF home showed consistently lower values for air leakage in these tests. The buildings otherwise provided similar data during testing, suggesting that the difference in values is due to greater airtight integrity of the ICF construction method. Testing on more homes is necessary to be conclusive. However, ICF construction shows promise as a tighter building envelope construction method.

INTRODUCTION

Insulating concrete form (ICF) is a new type of outside perimeter wall construction that utilizes interconnected blocks of hollow expanded polystyrene insulation filled with concrete. ICF potentially provides a structurally sound wall system with energy efficient advantages compared to traditional wood-framed walls, such as a higher insulation value (R-value), greater thermal mass, ground coupling, and reduced air infiltration.

One particular interest is the potential for reduced air infiltration. ICF construction differs from wood-frame construction in the way the walls and floors join. Figure 1 shows multiple components used to create a wood-framed outer wall, as well as the simple design of the ICF outer wall. Wall-to-floor joints are generally better sealed in an ICF home. Wood-framed homes use sheets of wallboard or sheetrock to create walls. The seams where these sheets meet and penetrations through the sheets (electrical outlets, plumbing, etc.) are locations for potential air leaks. ICF homes consist of a solid, contiguous unit that is seamless. These characteristics suggest that an ICF home may be more airtight compared to a traditional wood-frame home.

An experiment is being performed by the ORNL Buildings Technology Center to investigate the potential energy benefits of an ICF home compared to a wood-framed home.

MATERIALS & METHODS

Two side-by-side homes were constructed by Habitat for Humanity in Loudon, Tennessee, to conduct the experiment. One home is of wood-framed construction and the other utilizes the ICF method. Both homes are unfurnished and identical in configuration. Both homes have the same interior volume. However, the thicker walls of the ICF home create a larger outer perimeter. On June 22 and 23, 2000, tests were performed to determine the air tightness of the ICF constructed home compared to the wood-frame constructed home. Data collected were later analyzed and are presented in this report.

Utilizing standard air leakage testing methods (CGSB 1986) and equipment, including a newly released testing software package, an ORNL Building Technologies Center team performed blower door, duct blower, and pressure pan tests to measure air leakage of the homes, the duct systems, and the individual registers and their contributory ducts, respectively. The wood-framed home was tested on the first day, and the ICF home was tested on the following day. The test methods referenced above are designed to account for variable weather and indoor temperature conditions, so tests performed on different days are directly comparable.

Figure 1. Comparison of infiltration characteristics of a wood-framed and ICF house.
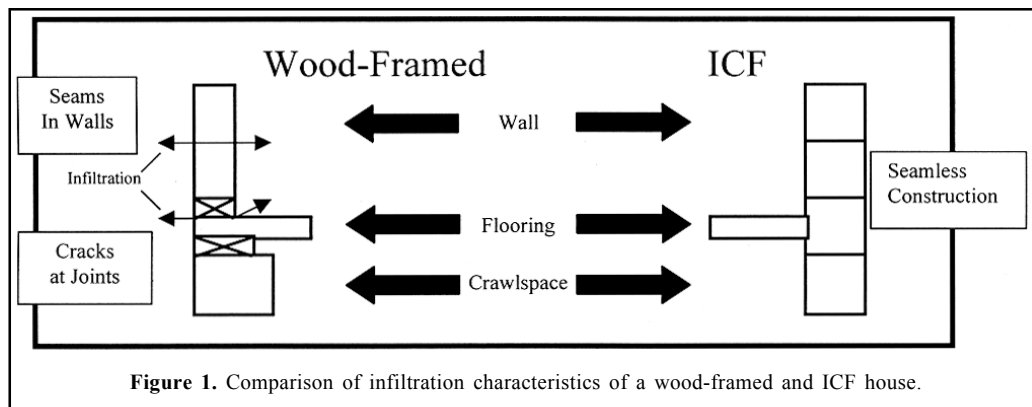
BLOWER DOOR MEASUREMENTS

Natural infiltration, generally caused by wind or stack effect, is impacted by duct leaks and mechanical ventilation and can be measured directly using tracer gas techniques. However, a blower door can be used to measure the leakage characteristics of a house under specified and controlled conditions. The blower door is an easier method to compare homes directly and can be used to estimate natural infiltration rates if desired. Standard values for infiltration flow rates, such as the cubic feet per minute of air flow at 50 Pa (cfm_{50}) and air exchanges per hour at 50 Pa (ACH_{50}) are based on measurements taken with a blower door.

A blower door measures the overall leakiness of a home by depressurizing the home to a standard differential pressure and calculating how much airflow is required to maintain that pressure.

The relation between airflow (Q) and pressure differential (Dp) is shown below by Equation (1) (ASHRAE 1997).

$$Q = C(Dp)^n \qquad (1)$$

Where,
Q = Air flow through the blower door fan (cfm)
C = Flow coefficient (cfm/Pa)
Dp = Pressure differential between inside of house and outside (Pa)
n = Flow exponent (dimensionless)

Traditionally, the blower door is used to determine leakage flow rates by maintaining a constant pressure differential of 50 Pascals (Pa) and measuring the corresponding flow rate through the blower door's fan. However, due to the fact that many variables, such as unstable gauges, wind, and temperature can make it difficult to maintain constant pressure differentials, one measurement does not provide a very accurate flow rate. Furthermore, it is not possible to measure at 4 Pa or even 10 Pa. Therefore, it is necessary test at multiple points and extrapolate desired data. A better method is to take multiple readings at decreasing pressure differentials, plot the data, perform a regression, and then calculate the flow rate at 50 Pa exactly.

By taking the logarithm of both sides of Equation (1), Equation (2) is obtained,

$$Q' = C' + nDp' \qquad (2)$$

which is the equation for a straight line. This equation can be used in the above procedure to return a calculated leakage value at the standard pressure differential of 50 Pa. While more accurate, this method is much more tedious and time consuming to perform with manual gauges and a pocket calculator. The BTC team was able to use a new software package that works in tandem with the blower door unit to take hundreds of readings in a very short period. Software on a laptop computer controlling the blower door starts at around 50 Pa and steps down by increments of 5 Pa until it reaches a minimum recordable flow rate around 15 Pa of pressure. The software then performs all calculations and returns the standard flow rates, along with other pertinent data.

The blower door test is helpful in determining how much air is flowing through various holes in the envelope. Equivalent Leakage Area (EqLA: Canadian standard based on 10 Pa household pressure) and Effective Leakage Area (ELA: LBNL standard based on 4 Pa household pressure) are values that describe the gross area of leaks measured in a home. However, these are artificial values in that they only indicate the amount of air being pulled into the house through all holes by the blower door, whereas in natural conditions air enters the envelope through some holes and escapes through other holes. Regardless, this method is informative in describing the amount of leakage occurring and quantifying the area of all sources.

For this experiment, the team wanted to perform blower door tests on just the walls themselves to determine if there was a difference in air-tightness. It was necessary to seal known leakage sites and leaks that may not be the same in each home. To do this, the team performed four sets of measurements in each home. At each of the four steps, the homes were sealed to a greater degree, ultimately arriving at a condition where the walls were isolated as best as possible from the rest of the home.

First, a standard blower door test of the whole house was conducted. Second, all duct registers and returns were sealed to exclude the duct system from the measurement. Third, ceiling holes such as those for attic access doors and bathroom fans were sealed to limit the leakage test to mainly exterior doorways, windows, and exterior walls. Finally, all windows (within the window frame) and doors were also sealed. At this point, the walls and their leakage locations were effectively isolated from the rest of the home. Areas that allow air to pass through walls and floorboards, such as holes cut for piping or electrical fixtures, are called penetrations.
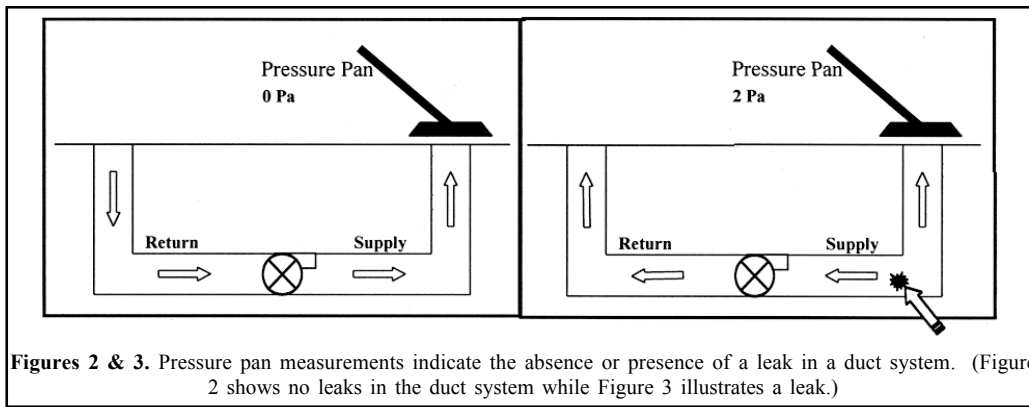
Figures 2 & 3. Pressure pan measurements indicate the absence or presence of a leak in a duct system. (Figure 2 shows no leaks in the duct system while Figure 3 illustrates a leak.)

Duct Blower Measurements

Duct blower tests were performed on each home to measure leakage experienced by the duct system. Similar to the blower door, the duct blower determines the required airflow into a sealed duct system to maintain a specified pressure differential. Two standard tests are usually performed using the duct blower 3-4 total duct leakage and duct leakage to the outside. While the former is helpful in determining total system integrity, the latter is much more important because air leakage to the outside has a significant impact on the overall efficiency of the HVAC system. Both total duct leakage and duct leakage to the outside were tested on each home.

First, total duct leakage can be calculated by allowing the home to experience zero pressure differential to the outside. This can be accomplished by having a door or window open. The duct blower fan is attached to the return register with all supply registers sealed. While a pressure differential of 25 Pa is maintained at the farthest register in the system, pressure across the duct blower fan is read and used to calculate a corresponding flow rate. This value can be determined by either a table provided by the duct blower's manufacturer or a digital pressure gauge calibrated for the specific duct blower.

For duct leakage to the outside, the blower door should be run in tandem to the duct blower, pressurizing the home to 25 Pa with respect to the outside. The duct blower is then run until there is no pressure differential between the duct system and the house. At this point, all air flowing through the duct blower is leaking to the outside. This flow rate can be also obtained by using tables or calibrated gauges. It should also be noted that the difference between total duct leakage and duct leakage to the outside is in fact duct leakage to the inside.

Pressure Pan Measurements

Pressure pan tests were performed on each home. These tests are used to identify the location of leaks, especially at the registers and in their tributary ducts, as well as to determine the similarity of duct leakage between the two homes. To perform the test, the blower door is used to depressurize the home to a differential of 50 Pa. Tools similar in shape to baking pans are used to cover individual registers and measure the pressure differential across them. If the duct system has no leaks, then the pressure differential should be zero (see Figure 2). This is because the duct is under the same pressure as the house. If there are leaks in the

register or tributary duct, a pressure differential usually between 1 and 10 Pa can be read because air is being drawn into the duct system near the register (see Figure 3). Pressure differentials between 0 and 1 indicate a tight register.

RESULTS

Blower Door

Results of the blower door tests for the two homes are shown in Table 1. Tests are labeled 1 through 4, identifying the four steps taken to isolate the walls as best as possible, and lettered "a" through "d" for any duplicate tests at that condition. Duplicates were taken at certain conditions to test the repeatability of the method. Flow-rate results at standard pressure differential of 50 Pa (cfm_{50}), Equivalent Leakage Area (EqLA) and Effective Leakage Area (ELA) are provided as calculated by the software. Flow

Table 1. Wood and ICF Construction Blower Door Test Data Summary
1. Blower door test of whole house.
2. Seal all duct registers and returns.
3. Seal all duct registers and returns, and penetrations.
4. Seal all duct registers and returns, penetrations, all windows and doors.
- cfm_{50} 3-4 Air leakage rate at standard pressure differential of 50 Pa.
- EqLA 3-4 Equivalent leakage area in square inches at standard pressure differential of 10 Pa.
- ELA 3-4 Effective leakage area in square inches at standard pressure difference of 4 Pa.
- C 3-4 Flow coefficient from Equation (1).
- n3-4 Flow exponent from Equation (1).
- R^2 3-4 Regression coefficient obtained from fitting the test data using Equation (1).

Wood

Test #	cfm_{50}	EqLA	ELA	C	N	R^2
W1	784	77.9	70.6	56.2	0.674	0.9992
W2	742	72.3	37.2	50.7	0.686	0.9994
W3a	593	55.6	28	36.9	0.71	0.9975
W3b	592	57.7	29.7	40.4	0.686	0.9938
W4a	566	56	29.1	40.1	0.667	0.9997
W4b	557	48	23	28.2	0.763	0.9963
W4c	558	56.5	29.7	41.9	0.662	0.9969

ICF

Test #	cfm_{50}	EqLA	ELA	C	N	R^2
C1a	726	73.7	38.3	54.8	0.660	0.9998
C1b	713	73.9	39.4	56.6	0.648	0.9998
C1c	696	71	37.5	53.1	0.658	0.9998
C1d	693	69.9	36.7	51.5	0.664	0.9998
C2	658	65	33.7	46.4	0.678	0.9999
C3	459	41.8	20.7	26.6	0.728	0.9992
C4a	447	42.1	21.3	28.2	0.707	0.9997
C4b	449	43.1	22	29.6	0.695	0.9995

Coefficient (C), Flow Exponent (n), and Correlation Coefficient (R^2) are also provided as calculated by the blower door software package and are all within acceptable ranges. Furthermore, the software's own internal check for error yielded no greater than a 1% average deviation for all tests, indicating that all the listed tests are valid.

Duplicate tests in Table 1 verify the precision of the testing method. Of these duplicate tests, none of the cfm_{50} values vary more than 3% from one another. However, one area of discrepancy is in the #4 tests of the wood home. It is evident from the data in Table 1 that the test W4b varies in C and n from tests W4a and W4c under the same conditions. While cfm_{50} is comparable, the different curve defined by Equation (2) for different values of C and n lead to different values of EqLA and ELA. Since the C and n values are different, they change the slope of the curve defined by Equation (2). The team was having trouble keeping a bathroom ceiling fan sealed during test W4b. It is likely that the reason for this variation is the faulty seal on the bathroom vent.

Table 2 shows the average flow rate for each test and differential flow rates between successive tests. It also shows the difference in flow rates between the Wood and ICF homes for each test. It is clear that the ICF home experiences a consistently lower flow rate for all tests, and, most importantly, shows a difference of 112.3 cfm in flow rate during test #4, when the walls are isolated as much as possible from the rest of the home.

Taking the difference of the average flow rates for each test reveals the actual leakage due to the items sealed in these tests. The data indicate that ducts contributed about forty to fifty cfm_{50} to the total leakage of the houses, while windows and doors contributed about thirty cfm_{50} or less. The large difference in leakage values between tests two and three are reasonable since only the duct registers were sealed for test two and numerous penetrations were sealed for test three including: attic access, two bath fans, dryer vent, refrigerator and clothes washer water connec-

tions. The leakage contribution due to doors, windows and doors, and other penetrations are about the same in each house, indicating a similarity and consistency in construction of the two houses.

Duct Blower

Table 3 shows both the total and outside duct leakage results for each home. Register pressure was close to 25 Pa as required by the testing standards. Flow rates from both the digital meter and the manufacturer's tables determined by the pressure recorded through the fan are shown as "Fan Pressure" in Table 3.

According to proposed and newly enacted standards in some states and utility programs, values for duct leakage to the outside should be no more than five percent of floor area or five percent of the total duct flow. For the 800 cfm system in these homes, a desired value for duct leakage to the outside is around 40 cfm at 25 Pa. Results from the duct leakage to the outside for both homes are close to the current agreed ranges for a tight system. This ensures that neither home suffers from shoddy construction methods or materials in its duct system. Values for duct leakage to the outside are not significantly different between the wood-framed and ICF homes.

There is also an interesting relation between total and outside duct leakage for each home. The difference of these two values is duct leakage to the inside. Both homes show that a significant portion of the total duct leakage is to the inside. The ICF home experiences a lower total duct leakage, and therefore also a lower duct leakage to the inside.

Pressure Pan

The results from the pressure pan tests are shown for both homes in Table 4. Most registers experienced a pressure differential less than 1.0 which is considered tight. High values at both returns are likely to be from a leaky return cabinet which acted as a plenum. Most noteworthy is the consistency of data between the two homes. Both results are mostly lower than one and consistent throughout. Although the values in the ICF home are all slightly lower than the values at corresponding resisters in the wood home, the difference is not very significant.

DISCUSSION

In comparing the two homes, it appears that the ICF home experiences less leakage than the wood-framed home. The blower door readings at all test conditions were consistently lower in the ICF home compared to the wood framed home. The homes appear to be identical in all aspects except for the type of exterior walls. Thus, the lower leakage rate in the ICF home appears to be a consequence of the tighter exterior wall construction. It remains

Table 2. House Air Leakage Rates (cfm_{50})

Wood			ICF			Wood - ICF	
Test	Average	Difference	Test	Average	Difference	Difference	% Change
W1	784.0		C1	707		77	-9.8
W2	742.0	42.0	C2	658.0	49	84	-11.3
W3	592.5	149.5	C3	459.0	199.0	133.6	-22.5
W4	560.3	32.17	C4	448.0	11.0	112.3	-20.0

Table 3. Wood and ICF Construction Duct Blower Test Data Summary
- Total 3-4 Total duct leakage.
- Outside 3-4 Duct leakage just to the outside.
- Register pressure 3-4 Pressure ducts pressurized to in making leakage measurements.
- Fan pressure 3-4 Pressure drop across calibrated blower fan.
- Meter flow 3-4 Flow rate determined from fan pressure using calibrated fan equations.
- Table flow 3-4 Flow rate determined from fran pressure using standard fan equations.

Wood				
Test	Register Pressure (Pa)	Fan Pressure (Pa)	Meter Flow (cfm)	Table Flow (cfm)
Total	25.5	390	125	111
Outside	25	56.4	48	42

ICF				
Test	Register Pressure (Pa)	Fan Pressure (Pa)	Meter Flow (cfm)	Table Flow (cfm)
Total	25.3	224	95	84
Outside	25.2	75	55	48

Table 4. Wood and ICF Construction Pressure Pan Test Data Summary

Wood		ICF	
Duct Name	Pressure Change	Duct Name	Pressure Change
Kitchen	0.6	Master Bath	0.2
Master	0.6	Master	0.3
Living Room (door)	0.6	Living Room (door)	0.2
Living Room	0.6	Living Room	0.4
Bedroom2	0.5	Bedroom2	0.4
Bedroom3	0.5	Bedroom3	0.3
Bath	0.5	Bath	0.1
Return	1.9	Return	2.6

to be seen how a year of settling and occupation of the homes will affect these conclusions. Tests after one year are scheduled as part of the experimental plan.

Data from the blower door tests followed expected patterns of infiltration values decreasing as more areas of the homes were sealed. Furthermore, multiple tests performed under the same conditions confirmed the repeatability of the tests. Therefore, the data appear reliable for analysis. ICF home values for infiltration at all levels were consistently lower than the wood-framed home. Most importantly, when the walls were isolated from the rest of the home as best as possible, the ICF home showed an infiltration rate 112.3 cfm lower than the wood-framed home. What is also interesting is that both homes show similar differences in flow rate between each test. This implies that the homes were built in a similar manner of quality. From this information we can conclude that this ICF home is tighter than the neighboring wood-framed home in general, and in particular because of the tighter ICF walls.

It should also be noted that the differential values for the sealing of windows and doors is very low in both homes. This suggests that, under the conditions that were used in this study, windows and doors are not the most critical zone in need of sealing when air leakage is a concern. Since ducts are also not leaky, the largest leaks are attributed to areas other than the ducts, windows and doors. While this idea is less valid with very old homes, it appears that a leaky home with fairly new windows and doors may experience significant air leakage from other areas. During the blower door tests on both homes, the team noticed leakage occurring at smaller penetration locations such as internal door jams and electrical outlets after usual leakage paths, such as penetrations for attic access and fixtures, were sealed.

Both homes show similar duct leakage to the outside. Individually, the homes experienced equal duct leakage to the inside and the outside. Neither amount was excessive, although the outside leakage is more critical. The duct system is not considered to be an important factor in the difference in infiltration between the two homes. Rather, the duct system has been shown to be very similar in both homes. This is valuable information to compliment the energy monitoring being performed on the homes.

Pressure pan tests did not indicate any major leaks in the duct system; however, the return register cabinet was identified as a leaky location. This cabinet could benefit from tighter construction and sealing. Both homes experienced low-pressure pan readings and remained consistent throughout the home.

Ease of use and dependability are two good qualities of the software used. The accompanying hardware equipment, including the control unit and the automatically controlled blower door, also performed well. Analysis of the data from the software showed that the tests were less tedious and more accurate than previous manual methods. The tests themselves provided data in a simple format that agreed with expected results for tests of this nature. Ability to effectively analyze the data was ensured by this fact. Results were both in compliance with industry standards as well as similar in value to each other (CGSB 1986). Moreover, duplicate tests showed similar results, supporting a consistency in the equipment and also reliability of the data.

The scope of this study was limited in its ability to produce a general conclusion on the air leakage attributes of an ICF wall since it consisted of only two homes. There are many possibilities as to why the air leakage reduction attributed to the ICF wall may be greater or less than that concluded in this test, including but not limited to: the possibility of hidden flaws in construction unseen by the ORNL BTC team, hidden leaks under duct insulation, faulty connection of joints and/or fixtures, etc. While every effort was made by the team to ensure consistency in testing between the homes, only repeatability in a number of homes would better ensure the validity of the seemingly evident conclusions.

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