ACHIEVING AIRTIGHT DUCTS IN MANUFACTURED HOUSING

Janet McIlvaine, Research Analyst
David Beal, Project Engineer
Neil Moyer, Principal Research Engineer
Dave Chasar, Senior Research Engineer
Subrato Chandra, Program Director
Florida Solar Energy Center
Cocoa, Florida

ABSTRACT

This Florida Solar Energy Center (FSEC) study, conducted under the auspices of the U.S. Department of Energy's Building America Industrialized Housing Partnership (BAIHP), compares mastic sealed duct systems to tape sealed systems by showing measured *total* duct leakage ($CFM25_{TOTAL}$ and Qn_{TOTAL}) and/or measured leakage *to the outside* ($CFM25_{OUT}$ and Qn_{OUT}) in 190 manufactured home floors or home sections.

All manufacturers were considering or actively working toward achieving duct leakage below 3% of the conditioned floor area (Qn_{OUT}=0.03), consistent with Energy Star Manufactured Homes criteria.

Previous field tests suggest that $CFM25_{OUT}$ accounts for about half of $CFM25_{TOTAL}$.

These data show that achieving $CFM25_{TOTAL}$=6% during production was generally correlated with achieving $CFM25_{OUT}$=3% in mastic sealed systems, but less reliably with taped systems. Cost for achieving duct tightness goals range from $4 to $8 including duct testing on the assembly line

INTRODUCTION TO BAIHP

Over the past 10 years, researchers at the Florida Solar Energy Center (FSEC) have worked with the Manufactured Housing industry under the auspices of the U.S. Department of Energy (DOE) funded Energy Efficient Industrialized Housing Program and the Building America (BA) Program (www.buildingamerica.gov). FSEC serves as the prime contractor for DOE's fifth Building America Team: the Building America Industrialized Housing Partnership (BAIHP) (www.baihp.org).

This Building America research builds on the work of FSEC's Buildings Research Division, which has conducted energy efficiency research, produced technical guidelines, and provided training for the various sectors of the construction industry for the past 25 years (http://www.fsec.ucf.edu/bldg/).

FACTORY VISITS

Data and findings presented here were gathered during 39 factory visits to 24 factories of six HUD Code home manufacturers interested in improving the energy efficiency of their homes. Researchers conducted tests on 101 houses representing 190 floors[1].

During initial factory visits, BAIHP researchers typically meet with factory managers for an introduction to Building America and the systems engineering approach to building better houses. Factory managers explain their objectives (eg achieve Energy Star), challenges they are facing (call backs, reoccurring moisture problems, etc), and conduct a factory tour for BAIHP researchers. During the tour, researchers observe assembly techniques and identify areas of potential improvement.

Researchers test completed duct systems in the factory and in finished houses, if available, to assess initial duct tightness. This creates a benchmark for gauging progress.

After the factory visit, BAIHP researchers provide a Trip Report detailing the findings of the visit, including test results, and recommendations for improvements.

After manufacturers have implemented BAIHP recommendations, researchers may return to the factory for reassessment. Depending on the success of implementation, additional recommendations and reassessment are sometimes needed.

---

[1] Unless specifically called out as a "floor assembly" or "floor system", the term "floor" in this document refers to a single wide manufactured home or one section of a multi-section manufactured home. Floors are typically 12-14' wide and up to 60' long.

CHARACTERISTICS OF DATA SET

During factory visits and fieldwork with new manufactured homes between 1996 and 2003, researchers tested 132 floors with mastic sealed duct systems and 58 floors with taped duct systems (Table 1). Depending on the stage of production and the objective of the testing, researchers measured total leakage only, leakage to the outside only, or both.

Table 1 Characteristics of Data Set

	Taped	Mastic	Total
Factories Visited			24
Total Visits			39
Manufacturers			6
Total Floors	58	132	190
Number of Tests			
$CFM25_{TOTAL}$ Tests	56	124	180
$CFM25_{OUT}$ Tests	30	86	116
Type of Test Conducted			
$CFM25_{TOTAL}$ Only	30	44	74
$CFM25_{OUT}$ Only	4	6	10
Both $_{TOTAL}$ and $_{OUT}$	26	80	106

DUCT TIGHTNESS GOAL

Standard testing procedure calls for measuring the air flow rate through a calibrated fan used to eliminate the pressure difference between the duct system and the house while the house is held at either natural conditions ($CFM25_{TOTAL}$) or in a steady state at -25pascals (pa)[2] with respect to the outside ($CFM25_{OUT}$) (Energy Conservatory, '93 and '96.)

The ratio of $CFM25_{OUT}$ to conditioned area can be expressed as *normalized duct leakage*, Qn. (Florida Department of Community Affairs, '98.) Qn is useful for comparing the relative tightness of duct systems in houses of dissimilar area.

$Qn_{OUT} = CFM25_{OUT}$ / conditioned area

BAIHP recommendations recommends reducing normalized duct leakage to the outside, Qn_{OUT}, to a number less than or equal to 3%.

Qn_{OUT},target = 3%

[2] Though test protocols can use pressurization to measure duct leakage, all the CFM25out and $CFM25_{TOTAL}$ tests discussed in this paper were conducted using depressurization.

The $CFM25_{OUT}$ test cannot be performed until the house is nearly finished. Researchers and factory staff need to assess duct system tightness during production, when the duct system is still accessible for repair, if needed. However, the $CFM25_{TOTAL}$ test can be conducted after the duct system is completed before it is concealed. Leaks can still be repaired without disturbing any finishes.

Thus, duct tightness goals for manufactured housing are set in terms of total leakage, $CFM25_{TOTAL}$, typically at 6% or less of conditioned floor area (Qn_{TOTAL}).

Qn_{TOTAL}, target = (Conditioned Area) X 0.06

The following equations can be used to determine the $CFM25_{OUT}$ and $CFM25_{TOTAL}$ targets for meeting these goals:

$CFM25_{TOTAL}$,target = (Qn_{TOTAL}, target)(Cond. Area)
$CFM25_{OUT}$,target = (Qn_{OUT}, target)(Cond. Area)

Example:

Let, Qn_{TOTAL},target = 6%
Qn_{OUT},target = 3%
Cond. Area = 900

$CFM25_{TOTAL}$,target = (Qn_{TOTAL}, target)(Cond. Area)
= (6%)(900)
= **54**

$CFM25_{OUT}$,target = (Qn_{OUT}, target)(Cond. Area)
= (3%)(900)
= **27**

The duct leakage targets for a 900 ft^2 floor are $CFM25_{TOTAL}$ = 54 and $CFM25_{OUT}$ = 27.

Rationale for Duct Tightness Goal

A compilation of findings from field studies around the country shows average savings from airtight duct construction in new and existing homes to be 15% cooling energy savings and 20% heating energy savings (Compilation of findings in Cummings, et al, '91 and '93, Davis '91, Evans, et al, '96, and Manclark, et al '96.) Field repairs in these studies were usually made using UL181 listed tape and/or mesh and mastic.

These savings are achieved at relatively low first cost (see Economics of Duct Tightening for Manufactured Housing below) compared to other energy improvements such as equipment efficiency and window upgrades. However, changes or refinements in the production process are often required.

Duct Tightness Goal Achievability

Among the earliest BAIHP data, four houses built by the same manufacturer in 1997 exemplify the achievability of duct tightness in the manufactured housing setting. Two were standard homes used as control homes for comparison to an "energy improved" model and a "health improved" model (Chandra, et. al., '98.) Standard manufacturing methods were changed to mastic and the 3% Qn_{OUT} leakage target was easily met (Table 2).

Table 2 Demonstration of Duct Tightness Achievability: Standard Production compared to 2 Improved Models 1997

	Area (ft^2)	$CFM25_{TOTAL}$	$CFM25_{OUT}$	Qn_{TOTAL}	Qn_{OUT}
Control Home	1600	118	84	7%	5%
Control Home	1280	126	89	10%	7%
Energy Home	1494	51	25	3%	2%
Healthy Home	1920	79	36	4%	2%

CHALLENGES TO ACHIEVING DUCT TIGHTNESS GOAL

The challenges most often encountered mirror those identified by BAIHP staff during fieldwork with moisture and uncontrolled airflow damaged manufactured homes (Moyer, et al, '01).

- Leaky supply and return plenums
- Misalignment of components, for example, floor boots not reaching or not being lined up with trunk ducts (in-line floor ducts)
- Free-hand hole cutting in duct board and sheet metal without templates, often with fabricated tools or utility knives
- Insufficient connection area at joints
- Mastic applied to dirty (sawdust) surfaces
- Insufficient mastic coverage
- Mastic applied to some joints and not others
- Loose strapping on flex duct connections
- Incomplete tabbing of fittings
- Poor tape application

RECOMMENDATIONS FOR ACHIEVING DUCT TIGHTNESS GOAL

- Apply tapes per manufacturer recommendations for surface prep, temperature, and application pressure applied with a squeegee.
- Seal joints with mastic and, when needed, fiberglass mesh
- Accurately located and cut holes for duct connections
- Fully bend all tabs on collar and boot connections
- Trim and tighten zip ties on flex duct connections to sheet metal collar with a strapping tool
- Institute quality control measures, such as pressure testing ducts during production, in addition to visual inspection.
- Provide return air pathways from bedrooms to main living areas.

IMPROVING DUCT TIGHTNESS

Researchers found variation among manufacturers related to duct system materials, layout, fabrication, assembly, sealing, equipment type, quality control and air handler position. The primary variable analyzed here is the duct sealing method.

Duct Materials

Manufactures typically install ducts made of sheet metal, duct board, and flex duct.

Duct board components, which are generally assembled in the factory, include supply ducts, return plenums, ceiling boots, distribution boxes, etc.

Flex ducts are used in conjunction with prefab sheet metal collars to connect duct board components. Flex ducts are secured to collars with plastic zip ties. Collars are secured to duct board with built in tabs that fold out around the edge of the duct board.

Sheet metal components, such as supply boots, are generally pre-fabricated by suppliers in standard sizes. Sheet metal trunk ducts are fabricated in the factory. Table 3 summarizes the duct materials represented in the data set.

Table 3 Duct Materials in Data Set		
	Tape Sealed	Mastic Sealed
Undocumented	5	0
Sheet Metal (some with Flex Components)	24	22
Duct Board (some with Flex Components)	29	110
Total Systems Tested	58	132

Recommended Duct Sealant

Regardless of duct material, BAIHP recommends sealing with mastic, an elastomeric material specifically made for permanently sealing the fabricated joints and seams in heating, cooling, and ventilating ducts and duct insulation. This is consistent with other building scientists. (Lstiburek, ’93. Cummings, et al, ’93. Andrews, ’01. MHRA, ’03.) The elastomeric properties of mastic (RCD, ’03.) allow it to expand and contract as the dimensions of the duct system change slightly during each cycle of heating or cooling.

The longevity of mastic yields a performance advantage over tape, the traditional material used for duct sealing. Whereas taped systems may perform well initially, they may become leakier over time if the adhesive fails due to material movement at the joints surface and/or temperature differences and changes. Mastic, on the other hand, tolerates the temperatures differences between inside and outside duct surfaces as well as the frequent temperature changes over the life of the system.

Quality Control: Tangible Success

An objective quality control strategy is essential to achieving tight duct construction. If air were visible to the naked eye, a visual inspection would reveal leakage sites in any given duct system. In the absence of visible air, managers and line workers will need to learn a way to evaluate their duct construction quantitatively using pressure-testing equipment common to building science.

Initially, a standardized duct test on the factory floor provides an objective evaluation of current practice, repairs, and process improvements. Ultimately, pressure testing all duct systems replaces subjective evaluation with a tangible, objective measure of success: total duct leakage, $CFM25_{TOTAL}$ or a ratio of duct leakage to conditioned area, Qn_{TOTAL}. These surrogate measurements are shown by this data and other field studies (Cummings, et al, ‘02. MHRA, ‘02) to substantially correlate with duct leakage to the outside of completed houses, the factory’s ultimate quality goal.

Manufacturers often cite the support of BAIHP as objective, third party experts as a major benefit. Some manufacturers have already adopted the test procedure into their production process to conduct their own in-house verification of duct system tightness. This leads to a higher quality product as well as accountability of both the factory and field work force.

Examination of a Single Factory’s Progress

BAIHP found duct tightness improvement to be an incremental process. For example, in one factory, the duct leakage measured during the first visit was Qn_{TOTAL}=10% in the floor mounted systems and 5% in the ceiling mounted systems (Table 4). BAIHP made recommendations for improving the floor systems and the factory managers set out to achieve the Qn_{TOTAL} = 6% goal, in preparation for building homes under the Energy Star Manufactured Homes Program.

Problems with the floor systems included misalignment of the trunk duct with the floor risers/boots cutouts; free hand hole cutting; insufficient mastic application to seal the floor boots, crossover collars, and furnace plenum; and loose straps.

Researchers recommended: circle cutting and strap tightening tools (for flex duct zip ties), improving placement of trunk ducts under riser holes precut in the sub-floor, using templates for cutting holes in the trunk duct to improve dimensional matching with the risers, and increasing the size of the bead of mastic applied to joints.

During the second factory visit, researchers found that alignment had improved. Other issues were still unresolved: holes were still being cut free hand, leading to a host of assembly difficulties, workers were confused about where to seal the furnace plenum, not all joints were being sealed, and some were not sealed completely.

Researchers tested two randomly selected sections with floor systems (Table 4) which did not meet the Qn_{TOTAL} = 6% goal. A trip report reemphasized the recommendations that had not been implemented.

The third visit to the factory found substantial improvement to the assembly of the floor duct system. Three randomly selected houses were tested: All three met the Qn_{TOTAL} = 6% goal (Table 4). This factory's experience echoes that of other factories that BAIHP has worked with.

Table 4 Test Results of 3 Visits to Same Factory

Visit #	Duct Location	Floors Tested	Qn_{TOTAL} (Goal=6%)
1	Flr/Belly	1	10%
1	Ceiling	1	5% **U**
2	Flr/Belly	1	7%
2	Flr/Belly	1	6.3%
3	Flr/Belly	2	5.4% **U**
3	Flr/Belly	2	4% **U**
3	Flr/Belly	2	3.8% **U**

MEASURED DUCT TIGHTNESS IMPROVEMENTS FROM IN-FACTORY REPAIRS

Of the 190 floors in this data set, 9 test results show improvements from repairs made to initially leaky systems (Table 5). Maximum improvement was a reduction of Qn_{TOTAL} from 11.7% to 5.5%. The least improved system was tightened from Qn_{TOTAL} of 8.1% to 7.1%. Qn_{TOTAL} was reduced an average of 3.5%, representing a 43% improvement in duct tightness. This is a very persuasive method of training factory personnel when conducted with a freshly produced duct system on the factory floor.

Table 5 Duct Repair Test Results

House ID#	Initial Duct Joint Sealant	Before Repair Qn_{TOTAL}	After Repair* Qn_{TOTAL}
AL5R	Tape	11.7%	5.5%
68	Tape	11%	4.9%
84	Tape	8.0%	4.8%
85	Tape	8.1%	7.1%
88	Tape	4.5%	3.3%
14	Mastic	6.4%	2.6%
47	Mastic	6.5%	4.4%
51A	Mastic	8.0%	2.6%
52A	Mastic	6.0%	3.6%
Average		7.8%	4.3%
Average Reduction to Qn_{TOTAL}			**3.5%**
*All system repairs made with mastic, not tape.			

The duct systems in Houses 14, 47, 51A, and 52A were assembled with mastic. However, the production was marred by problems such as inaccurate cutting, inaccessible joints, and misalignment of components. These problems occurred in other mastic sealed systems that failed to make the target Qn_{TOTAL} as described next in Duct Tightness Findings.

DUCT TIGHTNESS FINDINGS

Duct tightness data presented have been gleaned from BAIHP Trip Reports with some supplementary data from the preceding program, the Energy Efficient Industrialized Housing Project.

All duct systems tested were in newly manufactured homes using industry standard methods as delineated in the Minneapolis Blower Door and Duct Blaster User Guides (Energy Conservatory, '93 and '96.) and augmented by the Florida Home Energy Rating requirements where appropriate. (Florida Department of Community Affairs, '93.)

Average, maximum, and minimum duct leakage data are presented in Table 6, which also includes similar data from a study published by the Manufacture Housing Research Alliance for comparison (MHRA, '03.) Figures 1 and 2 show all data points for Qn_{TOTAL} and Qn_{OUT}.

For mastic sealed systems (n=132), average Qn_{TOTAL}=5.1% (n=124) with 85 systems achieving the Qn_{TOTAL} = 6% target (Fig. 4). Average Qn_{OUT}=2.4% (n=86) with 73 systems reaching the Qn_{OUT} = 3% goal (Fig. 5).

For taped systems (n=58), average Qn_{TOTAL}=8.2% (n=56) with 19 systems reaching the Qn_{TOTAL} = 6% target (Fig. 2). Average Qn_{OUT}=5.7% (n=30), more than double the mastic average, with 5 systems reaching the Qn_{OUT} = 3% goal (Fig. 3).

The average Qn_{OUT} found in this data for mastic sealed systems was 2.4%. This correlates with the Manufactured Housing Research Alliance's study, which found an estimated average Qn_{OUT} of 2.5% in 59 floors, tested after duct repairs at 16 factories (MHRA, '03). MHRA did not report the measured total leakage used to estimate leakage to the outside, leakage for taped systems, or leakage for systems before repair.

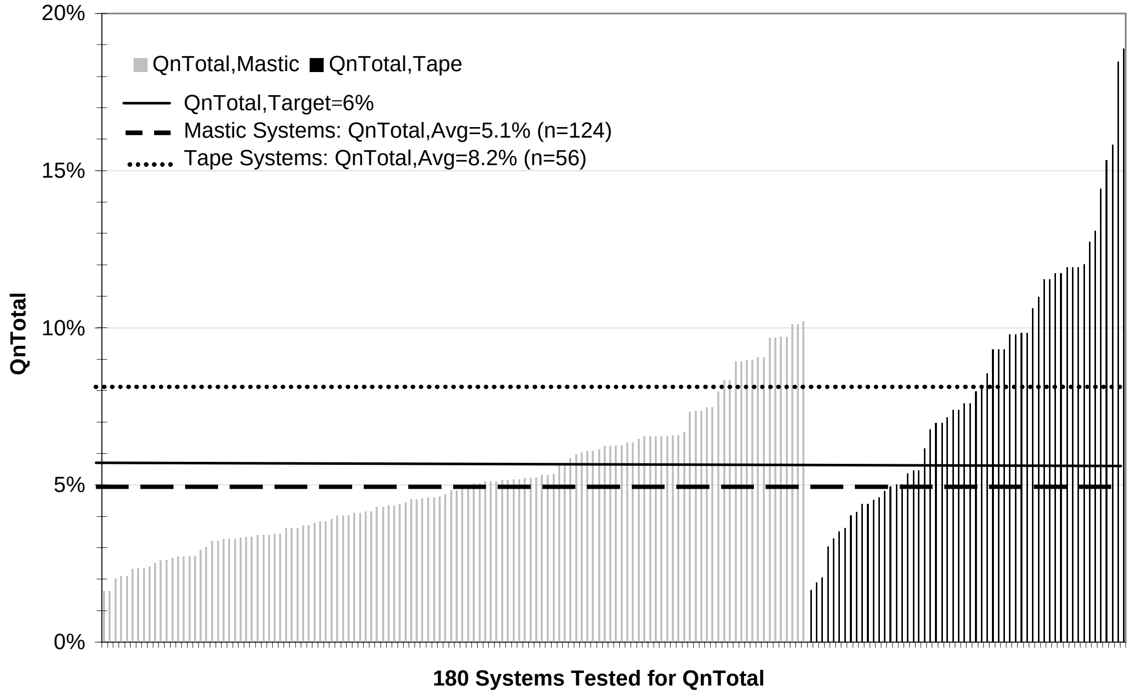

Figure 0 All 180 Qn_{TOTAL} data points. Qn_{TOTAL},Avg for taped systems (dotted line) was 8.2, well above the Qn_{TOTAL}=6% target (solid line) whereas for mastic systems Qn_{TOTAL},Avg=5.1%. Mastic data points exceeding the target are listed in Tables 7and 8.

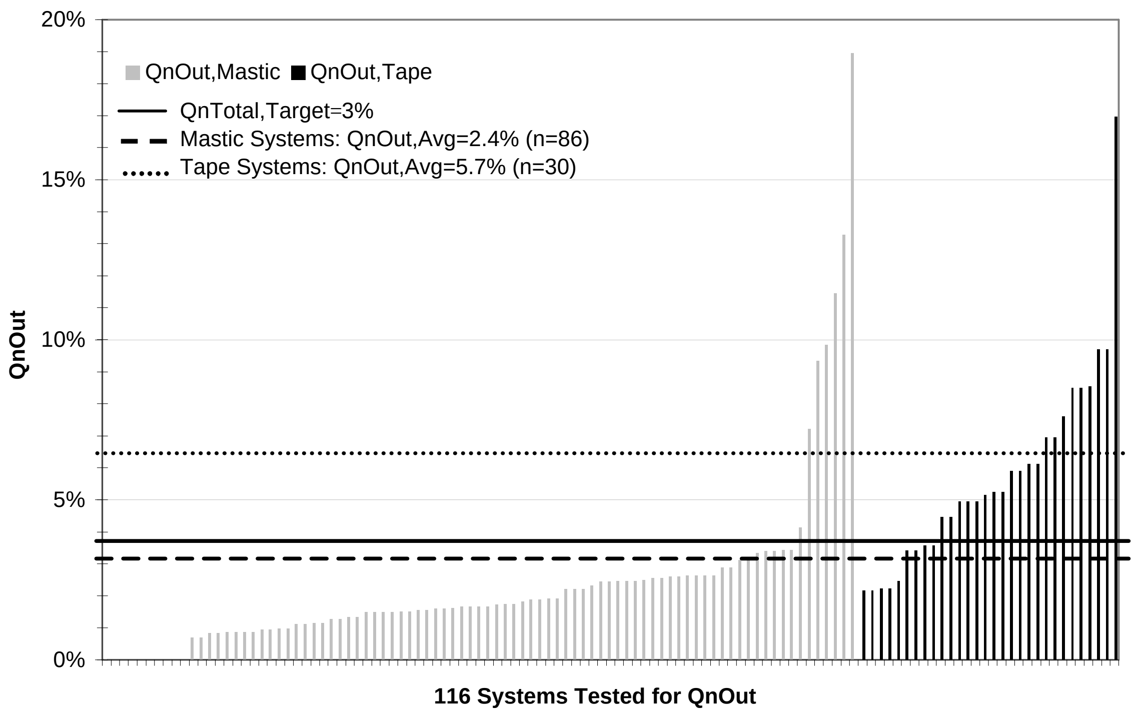

Figure 2 All 116 Qn_{OUT} data points. Five taped systems met the 3% Qn_{OUT} goal (solid line); however the Qn_{OUT},Avg = 5.7%, significantly exceeding the target. For mastic systems, the Qn_{OUT},Avg = 2.4%. Mastic systems exceeding the 3% Qn_{OUT} target are listed in Tables 8 and 9. Twelve mastic systems had $CFM25_{OUT}$ measurements below the threshold of instrument accuracy. (Energy Conservatory, '96.) These are reported as Qn_{OUT} ˜ 0% and do not register on this scale (note blank area on the far left portion of the X axis.)

Table 6 Summary of Findings With MHRA Findings

	BAIHP		MHRA
	Tape	Mastic	Mastic, Repaired
Floors Tested	58	132	59
$CFM25_{TOTAL}$ (cfm)	71 avg (n=56) 210 max 13 min	43 avg (n=124) 90 max 16 min	NA
$CFM25_{OUT}$ (cfm)	49 avg (n=30) 186 max 13 min	23 avg (n=86) 216 max 0 min	NA
Qn_{TOTAL}	8.2% avg (n=56) 18.9% max 1.7% min	5.1% avg (n=124) 10.2% max 1.6% min	NA
Qn_{TOTAL} = 6%	19	85	
Qn_{OUT}	5.7% avg (n=30) 17% max 2.2% min	2.4% avg (n=86) 18.9% max NA min	2.5%** avg (n=59)
Qn_{OUT}=3%	5	73	
Ratio of Qn_{OUT} to Qn_{TOTAL}	56% avg (n=30) 80% max 20% min	36% avg (n=80) 80% max 0% min	50% (apprx) avg (n=59) 60% max 24% min
Source	See References, Data Sources		(MHRA, '03)

*MHRA estimated Qn_{OUT}. See Qn_{OUT} compared to Qn_{TOTAL} below.

Mastic Sealed Duct Systems

Of the 190 floors tested, 132 had mastic sealed duct systems. Researchers conducted 124 $CFM25_{TOTAL}$ tests and 86 $CFM25_{OUT}$ tests.

Only total duct leakage was measured in 44 mastic sealed systems. Of those, 17 did not meet the Qn_{TOTAL} = 6% goal (Table 7). Problems centered on dimensional coordination of duct components and misaligned pre-cut register holes in sub-floor assemblies, incomplete mastic application, imprecise cutting, and incomplete joints (eg not all tabs bent).

Table 7 Mastic Sealed Systems Exceeding Target Leakage Rates

ID #	Floors	Qn_{TOTAL}	Problems Identified
27	2	10.1%	Holes in main trunk oversized boots
28	2	7.5%	Leakage at registers, furnace plenum, and joints. Many make-shift tools
51	1	8.0%	Leakage at registers, furnace plenum, and joints.
25	2	8.3%	No mastic on supply plenum
13	1		No mastic on furnace plenum
45	1	6.7%	Mastic applied incorrectly
26	2	7.3%	No mastic on furnace plenum
29	2	6.8%	Make-shift tools; poorly fitted holes
60	2	6.4%	Register installed under interior wall (inaccessible for sealing). Gaps in mastic application.
47	1	6.5%	Tab-over boots not in contact with trunk line. Gaps in mastic application.
50	1	6.1%	Leakage at registers, furnace plenum, and joints. Gaps in mastic application and boot connections.

Both total and outside leakage tests were conducted on 80 mastic sealed systems, of which 58 floors met both the Qn_{TOTAL}<=6% and Qn_{OUT}<=3% goals. The remaining 22 floors were divided into three groups (Table 8):

- Group 1: 14 Floors Met the Qn_{OUT} goal but not the Qn_{TOTAL}. The Qn_{TOTAL} range: 6.1% to 9.7%
- Group 2: 1 Floor that met the Qn_{TOTAL} but not the Qn_{OUT} goal. Qn_{OUT}=4.1%
- Group 3: 7 Floors that met neither goal.

Six of the seven floors that met neither goal were tested during two initial factory visits. One of the factories did not pursue BAIHP recommendations and the other is working toward achieving the Qn_{TOTAL} = 6%.

Table 8 Mastic Systems Exceeding Leakage Goals			
Group 1 (n=14) Achieved Qn_{OUT} =6% *but not* Qn_{TOTAL}=3%			
ID#	Floors	Qn_{TOTAL}	Qn_{OUT}
24	2	9.0% (Fail)	1.6% (Pass)
43	3	6.5% (F)	2.5% (P)
87	2	9.7% (F)	1.0% (P)
91	3	6.6% (F)	2.6% (P)
97	2	6.5% (F)	1.5% (P)
98	2	6.1% (F)	1.2% (P)
Group 2 (n=1) Achieved Qn_{TOTAL}=6% *but not* Qn_{OUT}=3%			
ID#	Floors	Qn_{TOTAL}	Qn_{OUT}
67B	1	6.0% (P)	4.1% (F)
Group 3 (n=7) Achieved Neither Qn_{TOTAL}=6% *nor* Qn_{OUT}=3%			
ID#	Floors	Qn_{TOTAL}	Qn_{OUT}
100	2	8.9% (F)	3.4% (F)
39	2	9.7% (F)	3.4% (F)
54A	1	9.1% (F)	3.3% (F)
99	2	6.3% (F)	3.1% (F)

Leakage to the outside *only* was measured in seven mastic sealed systems. One floor had leakage too low to measure. The six remaining floors failed to meet the Qn_{OUT} goal. This illustrates that mastic application alone will not ensure a tight duct system. Various problems in construction, installation, and sealing occurred in these systems as described in Table 9.

Qn_{OUT} compared to Qn_{TOTAL}

The MHRA study estimates Qn_{OUT} (Table 6) using a measured Qn_{TOTAL} multiplied by the ratio of Qn_{OUT} to Qn_{TOTAL} for a completed house from the same factory.

For example, if a completed house for Factory A was found to have Qn_{TOTAL}=7% and Qn_{OUT}=3.5%, then the Qn_{OUT} estimation factor for incomplete houses at Factory A would be 0.5 (7%/3.5%). The value of Qn_{OUT} to Qn_{TOTAL} ratios found by MHRA ranged from 24%-60% (MHRA, ‘03).

Field measurements in new site built homes (Cummings, et al, ‘02.) and many of MHRA’s field measurements in new manufactured homes show Qn_{OUT} is often approximately half of Qn_{TOTAL}, and in the absence of measured data from a factory, MHRA used 50% as the multiplier to estimate Qn_{OUT} from the measured Qn_{TOTAL} (MHRA, ‘03.) As mentioned earlier, the goal of Qn_{TOTAL}<= 6% originates from applying the 50% rule of thumb multiplier to obtain a Qn_{OUT}<=3% goal, which is the BAIHP recommended duct leakage level corresponding to the most stringent duct leakage level in the Manufactured Home Energy Star program.

Table 9 Mastic Sealed Systems Exceeding Target Leakage Rates			
ID#	Floors	Qn_{OUT}	Problems Identified
124 125	1 1	18.9% 13.3%	No mastic on return or supply plenum. Holes cut with large knife described Misalignment of components throughout
127 128 129 130	1 1 1 1	11.5% 9.8% 9.3% 7.2%	Tested in field shortly after set-up. All same manufacturer who is still in pursuit of Qn_{OUT} <=3% goal.

BAIHP data includes 26 taped systems that researchers tested for both total and outside leakage. The average ratio of outside leakage to total leakage was 56%, roughly agreeing with the rule of thumb. However, in the 80 mastic sealed systems, the average ratio of outside leakage to total leakage was somewhat lower than expected at 36%. There were 13 mastic sealed systems that met the Qn_{OUT} = 3% goal without meeting the Qn_{TOTAL} = 6% goal.

This lower than expected ratio is perhaps due to the improved sealing at joints between duct components but not between the house envelope and the air distribution system (e.g. joint of supply boots and subfloor or ceiling). Leakage at that joint is part of the total leakage, but tends to be eliminated when measuring leakage to outside.

Though the average ratio of outside leakage to total leakage in the mastic sealed systems was slightly lower than expected (36%), the range spanned 0% (no leakage or leakage too small to measure accurately) to 80%. The data strongly supports that achieving a Qn_{TOTAL} of 6% signifies that the Qn_{OUT} will be less than 3%. Only one exception was documented (Qn_{OUT}=4.1%).

ECONOMICS OF DUCT TIGHTENING IN MANUFACTURED HOUSING

Costs for implementing tight duct recommendations were reported by Palm Harbor Homes (Kessler, '03.) and Southern Energy Homes.

Mr. Bert Kessler, VP of Engineering, reported, "Based on research with BAIHP, Palm Harbor Homes implemented duct system testing and increased return air pathways from bedrooms to 50in2 per 100cfm supply air company-wide. Since this implementation started, PHH has manufactured 35,000 homes and has had no incidents of moisture related issues in homes installed in hot-humid climates. Additionally, air flow issues have been all but eliminated."

Kessler comments that, "The benefits of testing and return air requirements far exceed the cost, both to the consumer and the manufacturing facility." The target leakage level is Qn_{TOTAL}<=3% and return air requirements adopted by the manufacturer based on 50in2 for every 100cfm of supply air delivered to the space. Excluding the 1 time cost for duct blaster equipment, Kessler estimates average mastic materials cost at $2.90 and labor cost for the duct sealing and testing at $12.42, totaling $15.32 for a 28 X 76, 2026 ft2, 3 bedroom, double wide home. Per floor cost equaling half that or $7.66

Kessler notes that all duct systems manufactured by Palm Harbor Homes are pressure tested on the production line and that costs for implementing the tight duct procedure vary significantly from plant to plant based on when during the production process the duct testing takes place, the system layout, and previous production standards. This is illustrated in the following information from Craig Young of Palm Harbor's Florida Division (Young, '03.) who reports lower labor costs but higher material costs than Mr. Kessler reports for the company at large.

Mr. Young reported production department supervisor estimates to BAIHP, finding that the labor cost of applying the mastic to the duct system is $3.47 per floor and the labor cost of testing the duct system including setting up the equipment (Minneapolis Duct Blaster) is also $3.47 per floor. The incremental material cost compared to tape is estimated at $1 per floor for a total of $8 per floor.

Correspondence from Michael Wade, Director of Quality Assurance & Code Conformance, Southern Energy Homes (Wade, '03.)

Mr. Michael Wade Director of Quality Assurance & Code Conformance, Southern Energy Homes reported projected production of 8,000 homes in 2003. They test their duct systems to evaluate if their goal of Qn_{TOTAL} <= 3% has been achieved. Mr. Wade says, "The test procedure is so quick that we don't take testing labor cost into consideration." Material costs were stated to be $6 per floor compared to $2 per floor for tape, a total incremental cost of $4 per floor.

CONCLUSIONS

Reduced duct leakage has been proven to reduce homeowner utility bills while improving comfort, durability, and indoor air quality (Compilation of findings in Cummings, et al, '91 and '93, Davis '91, Evans, et al, '96, and Manclark, et al '96.) Duct leakage prevalence has been documented among site built homes (Cummings, et al, '91, '93, '03), new manufactured homes (Tyson, et al, '96. MHRA, '03), and manufactured homes in failure due to moisture and air flow control issues (Moyer, et al, '01).

BAIHP researchers measured total duct leakage ($CFM25_{TOTAL}$, Qn_{TOTAL}) and duct leakage to the outside ($CFM25_{OUT}$, Qn_{OUT}) in 190 new manufactured homes or sections between 1996 and 2003. Taped (58) and mastic sealed (132) duct systems are included. The data set is further characterized in Tables 1 and 3.

Factories implementing duct tightening recommendations showed steady progress and were able to consistently produce duct systems that met the target tightness of Qn_{TOTAL}<=6%.

80 floors with mastic sealed duct systems were tested for both total and outside leakage. 58 achieved both the Qn_{TOTAL} = 6% and the Qn_{OUT} = 3% goals. Only one system achieved Qn_{TOTAL} = 6% but not Qn_{OUT}<=3%. This exception had a Qn_{OUT}=4.1%. An additional 14 mastic sealed systems met the Qn_{OUT} = 3% while exceeding the Qn_{TOTAL} >6% goal. Duct leakage measurements and findings are further summarized in Tables 6-9 and Figures 1 and 2.

BAIHP researchers will continue to use the Qn_{TOTAL}<=6% target with manufacturers. The average ratio of outside leakage to total leakage in the mastic sealed systems was slightly lower than expected at

36%. This helps explain how some manufacturers not meeting the Qn_{TOTAL} = 6% goal still met the Qn_{OUT} = 3% goal.

Though measuring duct leakage to the outside is the only positive way to verify that the Qn_{OUT} goal has been met, BAIHP feels confident recommending the approach documented here for assisting home manufacturers with meeting the Qn_{OUT}<=3% goal. Of the 24 factories discussed in this paper, 22 were able to achieve the Qn_{TOTAL} = 6% and/or the Qn_{OUT} = 3% goals they set for duct tightness.

REFERENCES

Andrews, John, 2001. Better Duct Systems for Home Heating and Cooling. BNL-68167. Brookhaven National Laboratory, Upton, New York.

Cummings, J.B., C. Withers, L. Gu, J. McIlvaine, J. Sonne, P. Fairey, M. Lombardi, 2002. Field Testing and Computer Modeling to Characterize the Energy Impacts of Air Handler Leakage. FSEC-CR-1357-02, Florida Solar Energy Center, Cocoa, Florida.

Cummings, J. B., J. J. Tooley, N. A. Moyer, 1993. Duct Doctoring: Diagnosis and Repair of Duct System Leaks, DRAFT. Florida Solar Energy Center, Cocoa, FL.

Cummings, J. B., J. J. Tooley, N. A. Moyer, 1991. Investigation of Air Distribution System Leakage and Its Impact in Central Florida Homes. Contract Report, Florida Solar Energy Center, Cocoa, FL, FSEC-CR-397-91.

Davis, B. E., 1991. The Impacts of Air Distribution System Leakage on Heating Energy Consumption in Arkansas Homes. Arkansas Energy Office, Littlerock, Arkansas.

Energy Conservatory, 1993. Minneapolis Blower Door, Operation Manual, Model 3. Energy Conservatory, Minneapolis, Minnesota.

Energy Conservatory, 1996. Minneapolis Duct Blaster (Series B), Operation Manual, 8th Edition. Energy Conservatory, Minneapolis, Minnesota.

Evans, Richard A. and Robert J. Tsal. Basic Tips for Duct Design. ASHRAE Journal, July 1996.

Florida Department of Community Affairs and Florida Solar Energy Center, 1998. Class 1 Florida Energy Gauge Certified Energy Rater Training Manual, Version 1.3. Tallahassee, Florida.

Kessler, Bert, 2003. Written Correspondence dated July 30, 2003. Palm Harbor Homes, Addison, Texas.

Lstiburek, Joseph W., 1993. Bugs, Rot, and Mold II, *Humidity Control in the Humid South*. National Institute of Building Sciences, Washington, D.C.

Manclark, Bruce, and Bob Davis. Duct Improvement in the Northwest, Part II: Mobile Homes. Home Energy Magazine. Jan/Feb, 1996.

Manufactured Housing Research Alliance, 2001. Energy Star® Labeled Manufactured Homes: Design, Manufacturing, Installation, and Certification Process. MHRA, New York, New York.

Manufactured Housing Research Alliance, 2003. Improving Air Distribution System (ADS) Performance in Manufactured Homes. MHRA, New York, New York.

Moyer, Neil, D. Beal, D. Chasar, J. McIlvaine, C. Withers, S. Chandra, 2001. Moisture Problems in Manufactured Housing: Probable Causes and Cures. ASHRAE Conference Proceedings IAQ2001. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, Georgia.

RCD Corporation, 2003. Website http://rcdcorp.com/pd8.asp. Eustis, Florida.

Wade, Michael, 2003. Correspondence, May 30, 2003. Southern Energy Homes, Inc, Director of Quality Assurance & Code Conformance, Re: Construction of manufactured homes to be placed in hot and humid climates. Addison, Alabama.

Young, Craig, 2003. Correspondence, May 27, 2003. Palm Harbor Homes, Florida Division, Engineering Manager, Subject: Duct Mastic. Plant City, Florida.

DATA SOURCES

Beal, D., 2003. Correspondence, August 8, 2003. Unpublished test results for Oakwood Homes (Hillsboro and Killeen, TX) and Redman Homes (Plant City, FL). Florida Solar Energy Center, Cocoa, Florida.

Chandra, S., D. Beal, B. McKendry, 1998. Energy Efficiency and Indoor Air Quality in Manufactured Housing – Affordable Comfort Selected Readings, May 1998, pp. 1-4. Affordable Comfort, Inc., Waynesburg, Pennsylvania.

Tyson, J., L. Gu, M. Anello, M.V. Swami, S. Chandra, N. Moyer, 1996. Manufactured Housing Air Distribution Systems: Field Data and Analysis for the Southeast. FSEC-CR-875-96, Florida Solar Energy Center, Cocoa, Florida.

Trip Reports produced by the Building America Industrialized Housing Partnership for the following factory visits:

Testing and Factory Reviews		
Location	**Date(s)**	**Manufacturer**
Albemarle (NC)	April 2000, June 2000	Palm Harbor Homes
Alma (GA)	December 2002, May 2003	Fleetwood Homes
Auburndale (FL)	December 2002, May 2003	Fleetwood Homes
Austin	August 2001	Palm Harbor
Austin Plant 5	May 2003	Palm Harbor Homes
Austin Plant 7	February 2000	Palm Harbor Homes
Boaz (AL)	April 2000	Palm Harbor
Buda (TX)	May 2003	Palm Harbor
Burleson (TX)	February 2000, May 2003	Palm Harbor Homes
Casa Grande (AZ)	April 2000	Palm Harbor Homes
Douglas (GA)	December 2002, May 2003	Fleetwood Homes
Fort Worth	February 2000, April 2000, July 2000, May 2003	Palm Harbor Homes
Moultrie (GA)	April 2002	Oakwood Homes
Pearson (GA)	September 2000, December 2002, May 2003	Fleetwood Homes
Plant City (FL)	July 1997	Palm Harbor Homes
Safety Harbor (FL)	December 1999	Jacobson Homes
Seiler City (NC)	April 2000, May 2000	Palm Harbor Homes
Tempe	April 2000	Palm Harbor Homes
Waycross (GA)	July 2001	Clayton Homes
Willacoochee (GA)	December 2002, May 2003	Fleetwood Homes