FLORIDA SOLAR ENERGY CENTER®

Achieving Airtight Ducts in Manufactured Housing

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This body of research, spanning eight years, would have been impossible without the genuine desire of our industry partners to improve their products and their willingness to share their experiences with others. We are pleased to partner with them as they strive to achieve their goals. Our current list of BAIHP Partners can be found on our BAIHP website, www.baihp.org, under "Team Members."

Achieving Airtight Ducts in Manufactured Housing

EXECUTIVE SUMMARY

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) which can be found online at: *www.baihp.org*.

Data and findings presented here were gathered between 1996 and 2003 during 39 factory visits at 24 factories of six HUD Code home manufacturers interested in improving the energy efficiency their homes. Factory observations typically showed that building a tighter duct system was the most cost effective way to improve the product's energy efficiency.

BAIHP and others recommend keeping duct system leakage to the outside ($CFM25_{out}$) equal to 3% of the conditioned floor area, termed Qn_{out}. However, most homes seen in a factory setting cannot be sealed well enough to perform a $CFM25_{out}$ test. Results of many field tests suggest that $CFM25_{out}$ will be roughly 50% of total leakage ($CFM25_{total}$). Thus, to achieve a Qn_{out} of less than 3%, manufacturers should strive for a $CFM25_{total}$ of less than 6% of the conditioned area (Qn_{total}).

Researchers measured total duct leakage and/or duct leakage to the outside in 101 houses representing 190 floors (single wide equals one floor, double wide equals two floors, etc.). Ducts systems observed in these tests were installed either in the attic (ceiling systems) or in the belly (floor systems). Researchers tested 132 floors with mastic sealed duct systems and 58 floors with taped duct systems.

Of the 190 floors tested by BAIHP, the results break down thus: For mastic sealed systems (n=132), average Qn_{total}=5.1% (n=124) with 85 systems achieving the $Qn_{total} \leq$ 6% target (68%). Average Qn_{Out}=2.4% (n=86) with 73 systems reaching the $Qn_{out} \leq 3\%$ goal (85%). For taped systems (n=58), average Qn_{total}=8.2% (n=56) with 19 systems reaching the $Qn_{total} \leq 6\%$ target (34%). Average Qn_{Out}=5.7% (n=30), more than double the mastic average, with 5 systems reaching the $Qn_{out} \leq 3\%$ goal (17%).

The results show that, while it is possible to achieve the BAIHP Qn goals by using tape to seal duct work, it is far easier to meet the goal using mastic. What isn't illustrated by the results is the longevity of a mastic sealed system. The adhesive in tape can't stand up to the surface temperature differences and changes or the material movement at the joints and often fails. Mastic provide a much more durable seal.

Typical factory visits consist of meeting with key personnel at the factory, factory observations, and air tightness testing of duct systems and house shells. A comprehensive trip report is generated reporting observations and test results, and pointing out

opportunities for improvement. This is shared with factory personnel, both corporate and locally. Often, a factory is revisited to verify results or assist in the implementation of the recommendations.

The most commonly encountered challenges observed in the factories include:

- Leaky supply and return plenums
- Misalignment of components.
- Free-hand cutting of holes in duct board and sheet metal.
- 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.
- Improperly applied tape

Duct system recommendations discussed in this report include:

- Set duct tightness target Qn equal to or less than 6% total and 3% to outside.
- Achieve duct tightness by properly applying tapes and sealing joints with mastic
- Accurately cut holes for duct connections
- Fully bend all tabs on collar and boot connections
- Trim and tighten zip ties with a strapping tool
- Provide return air pathways from bedrooms to main living areas

Summary of BAIHP Approach to Achieving Tight Ducts in Manufactured Housing:

- Set goal with factory management of achieving Qn_{Out}<=3% using Qn_{Total}<=6% as a surrogate measurement while houses are in production.
- Evaluate current practice by testing a random sample of units
- Report Qn_{Total} and Qn_{Out} findings; make recommendations for reaching goals
- Assist with implementation and problem solving as needed
- Evaluate results and make further recommendations until goal is met
- Assist with development of quality control procedures to ensure continued success

Finally, duct tightness goals can be achieved with minimal added cost. Reported costs range from $4 to $8. These costs include in-plant quality control procedures critical to meeting duct tightness goals.

Achieving duct tightness goals provides benefits to multiple stakeholders. Improving duct tightness diminishes uncontrolled air (and moisture) flow, including infiltration of outside air, loss of conditioned air from supply ducts, and introduction of outside air into the mechanical system. Uncontrolled air flow is an invisible and damaging force that can affect the durability of houses, efficiency and life of mechanical equipment, and sometimes occupant health. With improved duct tightness, manufacturers enjoy reduced service claims and higher customer satisfaction, while homeowners pay lower utility bills, breathe cleaner air, and have reduced home maintenance.

Achieving Airtight Ducts in Manufactured Housing

September 2003

1. Building America Partnership

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*).

Building America complements 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/*).

2. Factory Visits, Data Collection, and Data Description

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].

Figure 1 Duct blaster used to test air tightness of duct systems during factory visits.

During an initial factory visit, 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, challenges they are facing (call backs, reoccurring problem, etc), and conduct a factory tour for BAIHP researchers. During the tour, researchers observe assembly techniques and identify areas of potential improvement.

[1] Unless specifically called out as a floor assembly, the term "floor" in this document refers to a single wide or one section of a multi-section manufactured home.

Researchers test completed duct systems (Fig. 1) in the factory and in finished houses (Fig. 2), if available, to assess initial duct tightness. This creates a benchmark for gauging progress as managers implement duct sealing and assembly recommendations.

Figure 2 BAIHP Researcher Neil Moyer sets up blower door for testing the air tightness of a manufactured house.

After the factory visit, BAIHP researchers provide the factory managers with a Trip Report detailing the findings of the visit, including test results, and making recommendations for improvements. Recommendations may cover heating and cooling equipment efficiency and installation, marriage line details, insulation installation, infiltration and moisture control strategies, window specifications, and duct system air tightening.

Duct System Air Tightness

Duct tightening is among the most commonly recommended improvements. It improves the indoor environment, durability, energy efficiency, and comfort of the home simultaneously. (Appendix B, *Duct Leakage and House Pressure Concepts*). The EPA Energy Star Program for Manufactured Homes also requires that duct leakage to the outside be reduced to below 3%, 5%, or 7% of the conditioned floor area (Qn_{out})[2] depending on the package of energy features selected (MHRA, 2001.)

Studies in new and existing site built homes have documented that duct leakage can be reduced to a Qn_{out} of less than 5% by sealing the joints with a combination of fiberglass mesh and mastic.

A compilation of findings from field studies around the country shows average savings from air tight 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.

Duct Sealing

Mastic is an elastomeric material specifically made for permanently sealing the fabricated joints and seams in heating, cooling, and ventilating ducts and thermal insulation. BAIHP recommends the water based formulae for installer safety and easier cleanup. Mastic is

[2] Note that total duct leakage includes all air losses from supply ducts and all air infiltration into the return ducts from both conditioned and unconditioned spaces. This test can be conducted as soon as the duct system is completed, even if the house (or section) is not finished. "Duct leakage to out" refers to air leakage from to the outside.

supplied in either buckets or tubes for application with a brush, trowel, or caulk gun. Some preparations include a fiber reinforcement component. The elastomeric properties of mastic allows it to expand and contract as the dimensions of the duct system change during each cycle of heating or cooling.

Mastic should be UL181 listed for the type of duct material/insulation being sealed. When sealing holes larger than ¼" a fiberglass reinforcing membrane (mesh) is used to cover the hole and form a bed for applying the mastic (RCD, 2003.) UL181 listed tape may be used in lieu of the mesh. Generally, this size hole does not occur in the factories *after* cutting quality and component alignment has been improved.

The longevity of mastic yields a performance advantage over tape. 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 the duct as well as the frequent temperature changes over the life of the system.

These savings and performance advantages are achieved at relatively low first cost (s*ee Economics of Duct Tightening for Manufactured Housing, p. 19*) compared to other energy improvements such as equipment efficiency and window upgrades.

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.

Duct System Recommendations

Duct system recommendations discussed in this report include:

- Set duct tightness target of Qn equal to or less than 6% total and 3% to outside. *Note that the ultimate real goal is the latter target, 3% to outside. Conventional wisdom estimates leakage-to-outside to be 50% of the total leakage. Thus the 6% total target serves as a surrogate for leakage-to-out when only leakage to outside can not be measured, such as during production or before set up is completed.*
- Achieve duct tightness by properly applying tapes and sealing joints with mastic and, when needed, fiberglass mesh
- Accurately cut holes for duct connections
- Fully bend all tabs on collar and boot connections
- Trim and tighten zip ties on flex duct with a strapping tool
- Provide return air pathways from bedrooms to main living areas

Data Collection and Duct Tightness Goals

BAIHP duct system testing follows building science standard test procedures using a calibrated fan (duct blaster) to depressurize the duct system to a specific pressure, in this case 25 pascals (pa). The amount of air in cubic feet per minute (cfm) needed to achieve this pressure is determined, yielding a measure of total system leakage at a standard test pressure. This measure is referred to as $CFM25_{total}$.

A further test can be performed after the house is completed by using another calibrated fan to simultaneously depressurize the house and the duct system to the same pressure. This eliminates air flow between the two, yielding a meaure of system leakage to the outside at the same standard test pressure. All duct leakages measured during this test involves air from outside the conditioned space. This measure is referred to as $CFM25_{out}$. A low leakage to the outside is generally the ultimate objective since leakage to the house is considered much less detrimental to air quality, durability, comfort, and energy efficiency. To have “substantially leak free ductwork”, BAIHP recommends keeping system leakage to the outside below a $CFM25_{out}$ measurement equal to 3% of the conditioned floor area (Qn_{out}).

However, the $CFM25_{out}$ test can not 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. Based on the assumption that only a portion of the total leakage will be lost to the outside, duct tightness goals for *production* are set in terms of total leakage, $CFM25_{total}$, typically 6% of conditioned floor area (Qn_{total}) as illustrated in the following example.

Determining Duct Tightness Targets Example:
For a house of conditioned area = 1800 ft^2
Target Total Duct Leakage: (CFM25Total) $\leq$ (1800 ft^2)(6%) $\leq$ **108 cfm**
Target Duct Leakage to Outside: (CFM25Out) $\leq$ (1800 ft^2)(3%) $\leq$ **54 cfm**

3. Observations

Researchers find variation among manufacturers related to duct system materials, layout, fabrication, assembly, sealing, quality control and air handler position. The primary distinction focused on in this data set is the duct sealing method. 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, or both.

Table 1 Characteristics of Data Set

	Taped	**Mastic**	**Total**
Factories Visited			24
Total Visits			39
Manufacturers			6
Number of Tests			
Total Floors	58	132	190
$CFM25_{Total}$ Tests	56	124	180
$CFM25_{Out}$ Tests	30	86	136
Type of Test Conducted			
$CFM25_{Total}$ Only	30	44	74
$CFM25_{Out}$ Only	4	6	10
Floors Tested for Both	26	80	106

Duct Layout
Ducts systems observed in these tests were installed either in the attic (ceiling systems) or in the belly (floor systems). *Perimeter* floor systems have a main supply duct with smaller run-out ducts extending to the edges of the house. *In-line* floor systems have a main supply duct that is directly connected to supply registers with floor boots.

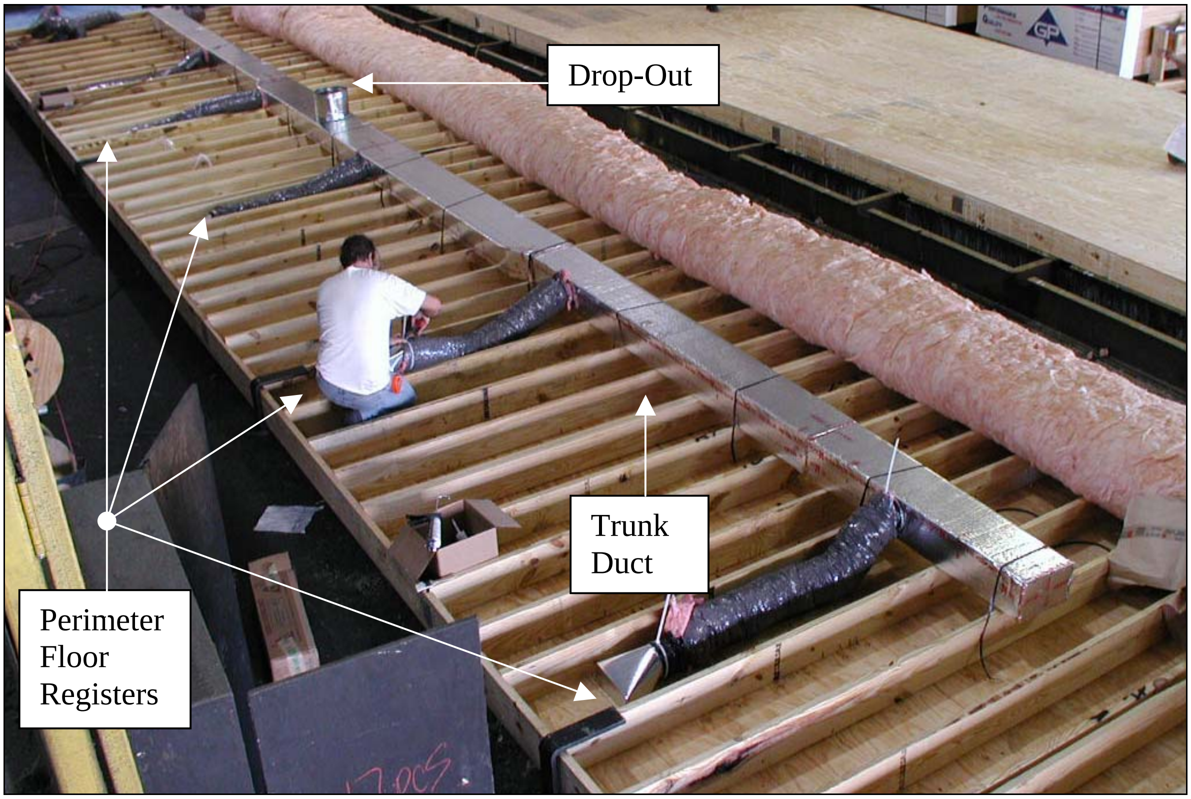


Figure 2 Duct assembly stations become a focus of improvement and quality control when factories strive to meet to qualify for Energy Star. Photo shows perimeter floor duct system with flex duct runs from duct board trunk to registers. Note this floor assembly will be flipped over after insulation is completed.

Occasional a "baby duct" will be run to serve a room that doesn't intersect the main supply trunk, such as a master bath or a laundry room. The data set represents a mixture of ceiling and floor systems, both perimeter and in-line layout, as summarized in Table 2.

Table 2 Duct Location and Layout in Data Set

	Taped	**Mastic**	**Total**
Undocumented	1	0	1
Overhead Systems	25	44	69
Floor Systems	32	88	120
Floor Perimeter	*2*	*8*	
Floor Inline	*1*	*34*	
Floor Undocumented	*29*	*46*	

Total Systems Tested	**58**	**132**	**190**

Air Handler Position and Connection to Duct System
Heating and cooling systems are either package units or split systems.

In homes designed for *package systems*, a duct drops from a central return plenum through the belly into the crawl space for connection to the package unit during set-up. The supply ducts, one from each section of the house, have a similar drop into the belly for connecting to the package unit. Thus, each section is directly connected to the main supply trunk. In overhead duct systems, this connection is sometimes made in the attic during set-up.

In homes designed for *split systems*, an air handler with a central return is installed during production. If the house is a multi-section unit with floor ducts, a drop-out collar is installed near the air handler in each trunk duct for tying the non-air handler section(s)'s supply ducts into the air handler. These are connected during set using a cross over duct (flex duct) in the crawl space for floor systems. Multi-section overhead systems are often connected through the attic during set-up.

Multiple returns are rare. Through-the-wall grills are sometimes used to provide a passive *return air path* from bedrooms. Researchers have observed that the HUD Code requirement of $1in^2$ of return air area for every $5ft^2$ of floor area served is not always adequate to prevent the main body of the house from depressurizing when bedroom doors are closed. BAIHP highly recommends adequate return air provisions to all bedrooms using passive, through wall grills or ducting from bedroom ceiling to main body ceiling.

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 floor 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		
	Taped	**Mastic**
Undocumented	5	0
Sheet Metal with Flex	24	22
Duct Board with Flex	29	110
Total Systems Tested	**58**	**132**

4. Challenges to Achieving Duct Tightness Recommendations

After BAIHP makes recommendations in a Trip Report, the factory staff work out solutions to the problems identified. Often, problems identified during a test can be quickly located in other duct systems on the production line. The problems most often encountered mirror those identified by BAIHP staff during field work with moisture and air flow damaged manufactured homes (Moyer, et al, 2001). The most commonly encountered challenges include:

Figure 4 No mastic on return duct in plenum serving packaged heating and cooling unit. Mastic used elsewhere in the plenum and throughout house.

- Leaky supply and return(Fig. 4) plenums
- Misalignment of components (Figure 5), for example, floor boots not reaching or not being lined up with trunk ducts (in-line floor ducts)
- Free-hand cutting of holes in duct board and sheet metal without templates, often with “home made” tools or utility knives (Fig. 6), for example, a hole for a crossover collar not being round creates a poor collar connection, holes in trunk duct for floor boots cut too large for floor riser, creating a hard-to-seal hole)
- Insufficient connection area at joints (Fig. 5, bottom), for example, supply plenum and drop-out collar that are same dimension as the trunk duct.
- 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 (Fig. 7, bottom)
- Poor tape application

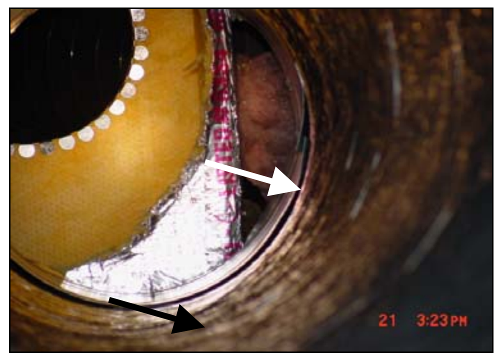


Figure 5 *Above* Misalignment of round duct to round cutout. Arrow shows where components should mate. *Below* Misalignment/insufficient connection surface at round duct collar to rectangular duct.

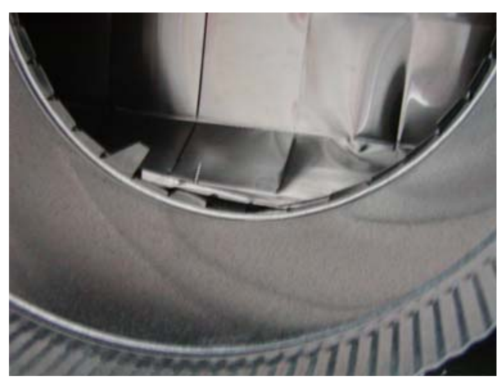


Figure 6 *Left* Holes cut free hand do not mate well with duct system components. Note round duct is jammed into an oval shaped cut out. *Right* Imprecise rectangular cutout for ceiling register creates poor joint.

5. Achieving Duct Tightness Recommendations

Many of the manufacturers working with BAIHP are striving to meet the quantitative goals set by the EPA Energy Star Program for Manufactured Homes. The program provides compliance paths for homes with three levels of duct leakage to the outside $Qn_{out} \leq 3\%$, 5%, or 7% (MHRA, 2001.)

Among the earliest BAIHP data, four houses built by the same manufacture 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., 1998.) Standard manufacturing methods were changed to mastic and the 3% Qn_{out} leakage target was easily met (Table 4).

Table 4 Demonstration of Duct Tightness Achievability
Standard Production compared to 2 Improved Models 1997

	Area	$CFM25_{total}$	$CFM25_{out}$	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%

Repair Improvements to Taped and Mastic

Of the 190 floors in this data set, 9 test results show improvements from repairs made to initially leaky systems (Table 5). This is a very persuasive example for factory personnel when conducted on a freshly produced duct system on the factory floor. This also shows the iterative problem solving process that BAIHP researchers use with factory staff to foster improvement in performance and production procedures.

For a description of improvements implemented at a single manufactured housing plant, see Appendix A.

Tightness of all 9 systems was improved by BAIHP repair (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.

Table 5 Duct Tightness Improvement Measurements.

House ID#	Duct Assembly Method	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%**

**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 other problems such as inaccurate cutting, inaccessible joints, and misalignment of components. These problems occurred in other mastic sealed systems which also failed to make the target Qn_{total} (see *Duct Tightness Data*).

Unit 14 illustrates BAIHP's iterative approach to working with factories. Unit 14 was a section of a double wide manufactured house containing an air handler for a split heating and cooling system. Initially, it showed duct leakage of 10.6% (Qn_{total}) on the air handler side. Researchers removed the air handler fan and connected the duct testing equipment directly to the duct system to quantify how much of the leak was associated with the unit itself. This dropped the $CFM25_{total}$ to 33cfm bringing the Qn_{total} to 6.4%, still too high to meet the tightness target of less than 6%.

Upon investigation, researchers and factory staff found holes in the main trunk line that were cut much larger than the connecting floor boots, too large to seal with standard mastic practice in use on the production line. The holes had been left open with no attempt to seal them. Researchers used fiberglass mesh and mastic to build up patches over the holes. $CFM25_{total}$ dropped another 29cfm bringing the Qn_{total} to 2.6%, well within the target zone.

Similar holes were found on the non-air handler side of the double wide suggesting that this was a systemic production problem. Improved cutting using a template to match supply boot dimensions was recommended.

A subsequent factory visit a month later found only one out of nine tested floors did not meet the $Qn_{total} \leq 6\%$. Qn_{total} measurements fell from the original 10.6% to: 2.3%, 2.7%, 3.9%, 3.6%, 4.4%, 4.5%, 4.5%, 5.8%, and 6.4%.

This result is exactly the desired effect of the BAIHP approach:

- Introduce Building America Industrialized Housing Partnership and systems engineering
- Build collaborative relationship with industry partners to solve problems
- Set goals with factory managers
- Quantify duct tightness resulting from existing practices
- Identify opportunities for improvement
- Report findings and make recommendations
- Assist with implementation when needed (e.g. training, problem solving for production process)
- Reevaluate to assess progress until goals are reached
- Implement factory quality control procedures, including pressure testing, to sustain success

Commonly Implemented Improvements

BAIHP researchers have observed that certain aspects of duct system fabrication must be addressed, in addition to the change from tape to mastic, in order to consistently deliver a substantially leak free duct system. Data compiled here show that manufacturers have consistently achieved duct tightness goals by implementing correct mastic application, improved cutting precision, better dimensional coordination between duct system components as well as between ducts and the house. The following list represents steps commonly taken by manufacturers to achieve their duct tightness goals:

All systems

- Train supervisors and line workers on air flow concepts
- Systemize the duct assembly process
- Use circle cutters and templates for standard duct cutouts
- Use mastic in a form that fits with the production process (tubes/buckets)
- Seal joints with a “pinky” size bead of mastic
- Seal the duct to the house air barrier (ceiling drywall or floor deck)
- Seal joints in return and supply plenums
- Institute quality control measures, such as pressure testing ducts during production, in addition to visual inspection

Floor System (Typically Sheet Metal) Improvements:

- Replace tape with mastic and, when needed, fiberglass mesh
- Ensure the supply plenum is well attached and thoroughly sealed to the trunk duct with mastic
- Select trunk duct dimensions that allow for slight misalignment of floor register cutouts without creating a failed joint.
- Improve alignment of floor register cutouts with trunk and branch ducts

- Provide adequate attachment area (tabs on all components should be fully bent)
- Use templates to cut holes in trunk ducts for floor risers
- Fully bend tabs on floor risers

Ceiling System (Typically Duct Board and Flex Duct Improvements)

- Use circle cutter to cut hole in duct board for flex duct collar
- Provide adequate attachment area around collar cut outs to allow all collar tabs to be fully bent.
- Lay generous bead of mastic (about the size of smallest finger) into corner where the flange meets the main body of the collar.
- Press collar into duct board hole. Mastic should spread.
- Spread mastic to completely cover collar flange and beyond edge of collar flange about ½".
- Slide inner line of flex duct onto collar past the positioning ridge and secure with a plastic zip tie trimmed with a tensioning tool.
- Slide outer lining up as close to the collar flange as possible and secure with a plastic zip tie trimmed with a tensioning tool.
- Remove excess flex duct, this can result in kinked supply runs.

6. Duct Tightness Data

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.

Testing Protocol

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 and augmented by the Florida Home Energy Rating requirements where appropriate.

Factory Visits and Test Results Summary

FSEC-BAIHP data spans 1996-2003 and includes test results from 39 visits to 24 factories of six HUD Code home manufacturers (Table 5). Researchers conducted tests on 101 houses representing 190 floors[3]. The data is a compilation of test results from standard production duct systems, repaired to improved production systems.

For a description of improvements implemented at a single manufactured housing plant, see Appendix A.

Average, maximum, and minimum duct leakage data are presented in Table 6 and Figure 7 with similar data from a study published by the Manufacture Housing Research

[3] Unless specifically called out as a floor assembly, the term "floor" in this document refers to a single wide or one section of a multi-section manufactured home.

Alliance for comparison (MHRA, 2003.) Figures 8-11 show all data points for Qn_{total} and Qn_{Out}. for taped systems (Fig. 8 and 9) and mastic sealed systems (Fig. 10 and 11).

For mastic sealed systems (n=132), average Qn_{total}=5.1% (n=124) with 85 systems achieving the $Qn_{total} \leq 6\%$ target (Fig. 10). Average Qn_{Out}=2.4% (n=86) with 73 systems reaching the $Qn_{out} \leq 3\%$ goal (Fig. 11).

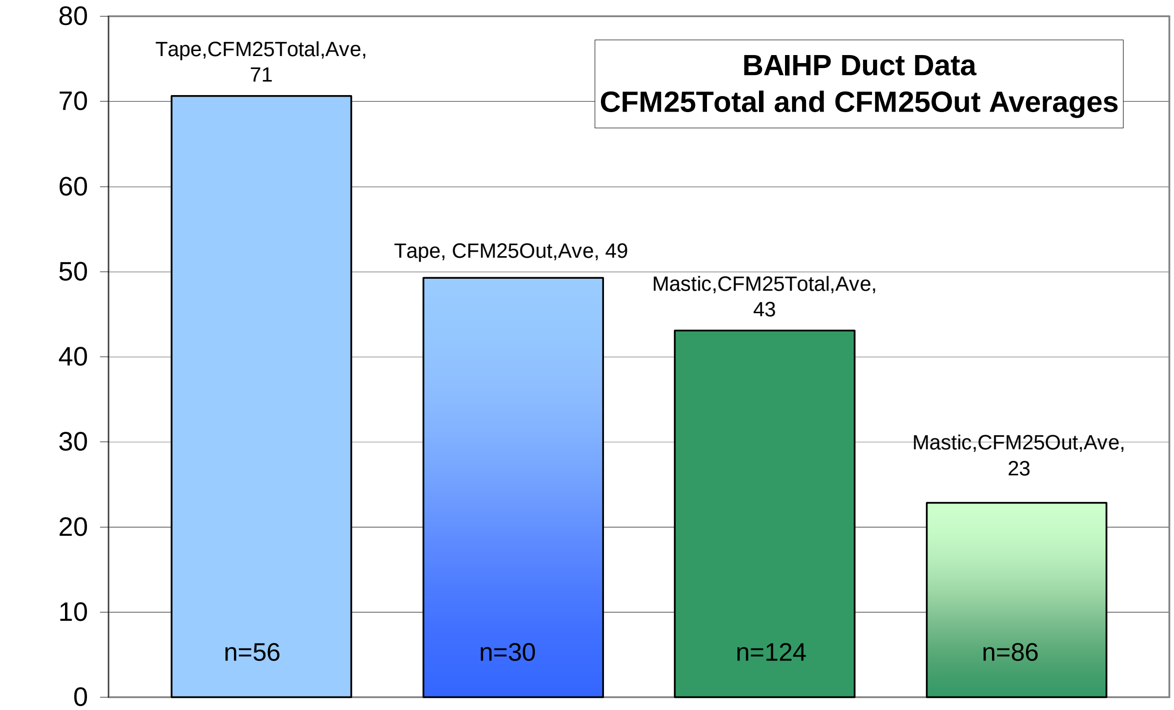
For taped systems (n=58), average Qn_{total}=8.2% (n=56) with 19 systems reaching the $Qn_{total} \leq 6\%$ target (Fig. 8). Average Qn_{Out}=5.7% (n=30), more than double the mastic average, with 5 systems reaching the $Qn_{out} \leq 3\%$ goal (Fig. 9).

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, 2003). MHRA did not report the total leakage (measured) used to estimate leakage to the outside, leakage for taped, or leakage for systems before repair.

Table 6 Summary of Findings (*see also, Figures 7-11*)

	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
$Qn_{total} \leq 6\%$	19	85	
Qn_{Out}	**5.7% avg** (n=30) 17% max 2.2% min	**2.4% avg** (n=86) 18.9% max unmeasurable min	**2.5%** avg** (n=59)
$Qn_{out} \leq 3\%$	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, 2003)

*Floor refers to a single wide or one section of a multi-section manufactured home.
**MHRA estimated Qn_{out}. see *Qn_{Out} compared to Qn_{total}*, p. 17



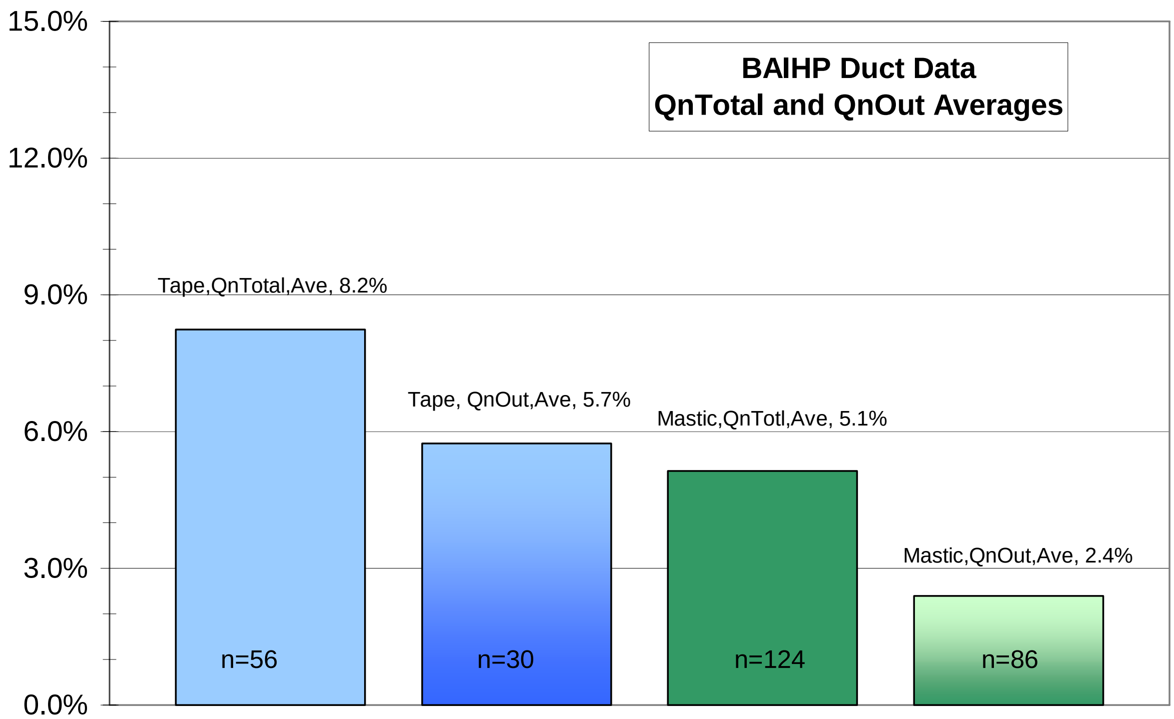


Figure 7 BAIHP Duct Data Averages

Top: Averaged $CFM25_{Total}$ and $CFM25_{Out}$ data show that mastic sealed systems were tighter than taped systems in both total leakage and leakage to the outside.

Bottom: Averaged Qn_{total} and Qn_{out} data show that mastic sealed systems, on average, met both the total leakage and leakage to outside goals whereas the taped systems met neither.

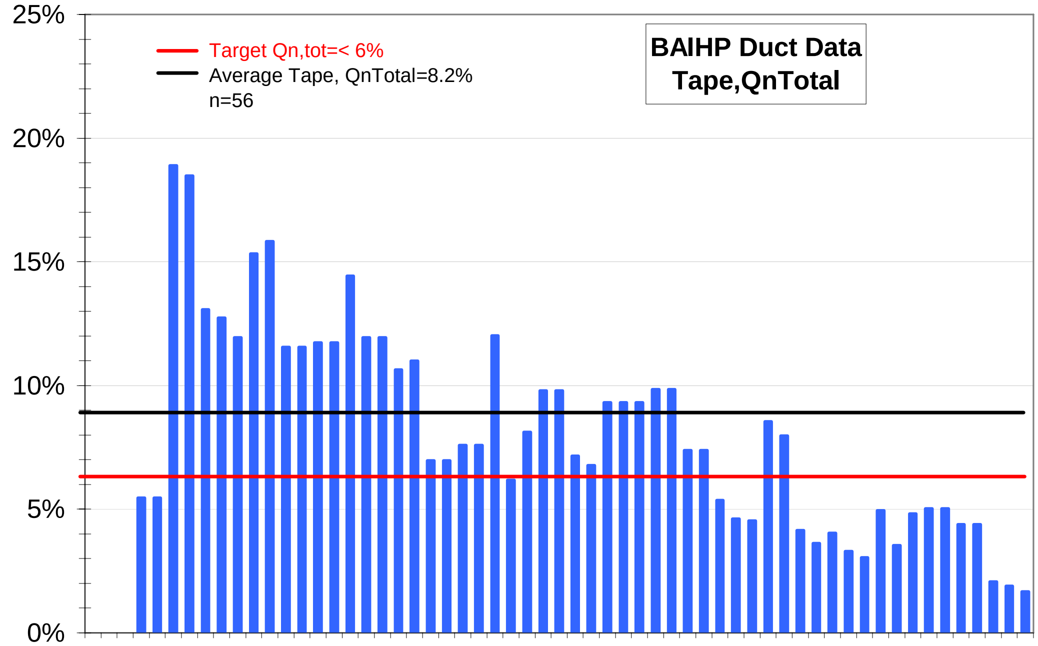


Figure 8 All Qn_{total} data points for taped systems. Note that average (black line) is well above target (red line). 19 tape sealed systems met the 6% Qn_{total} goal.

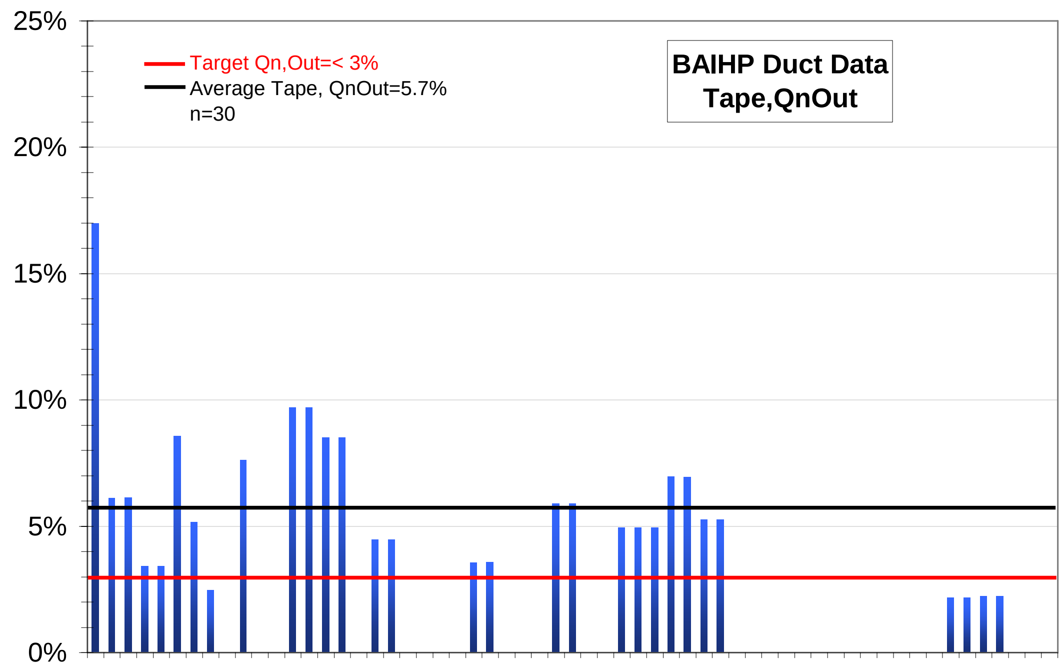


Figure 9 All Qn_{Out} data points for Taped systems. Note that 5 taped systems met the 3% Qn_{out} goal.

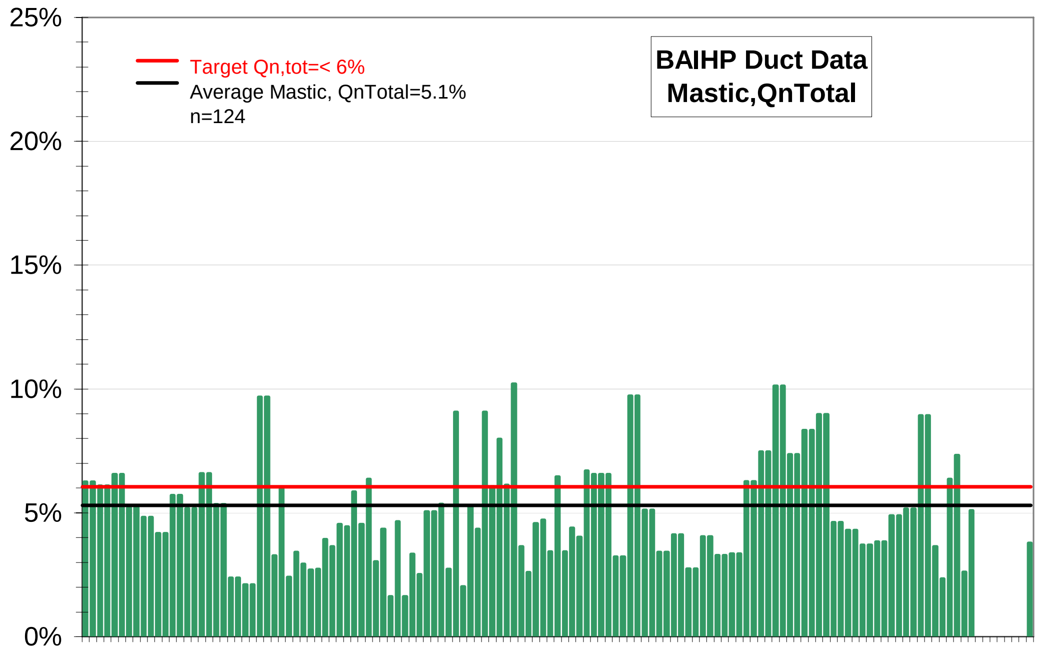


Figure 10 All QnTotal data points for mastic systems. Red line signifying target QnTotal<=6%. Black line shows the average QnTotal (5.1%) for mastic sealed systems. Data points exceeding the target are listed in Tables 7 and 8.

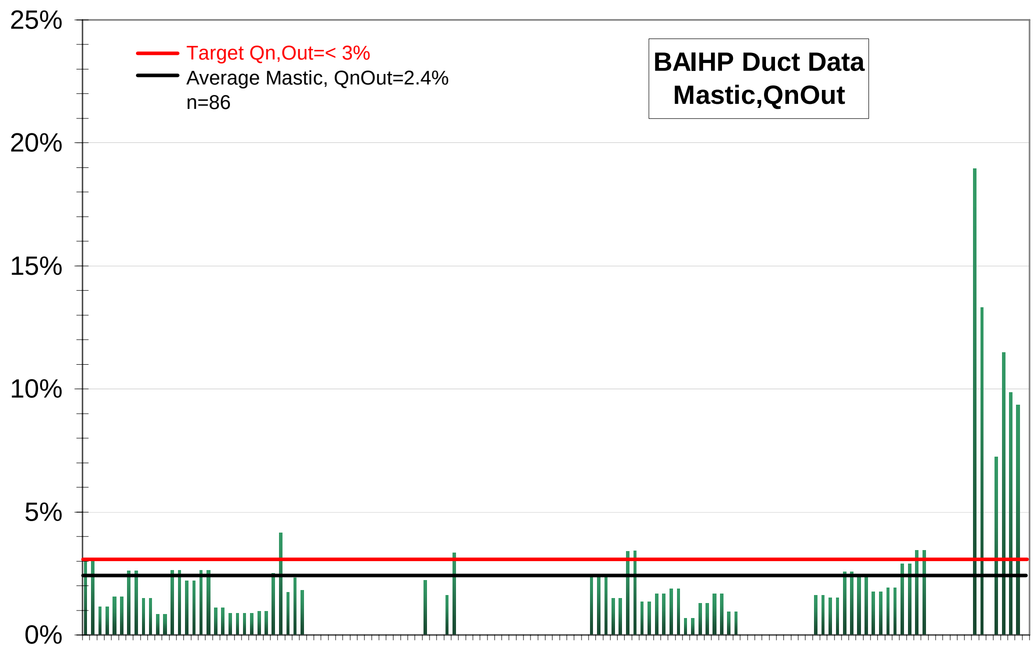


Figure 11 All Qn_{Out} data points for Mastic systems. Instances of $CFM25_{Out}$ being too small to measure accurately are reported as 0% leakage (n=12) and do not show up on this graph. Data points exceeding the 3% Qn_{Out} target are listed in Tables 8 and 9.

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.

Total duct leakage only was measured in 44 mastic sealed systems. Of those, 17 did not meet the $Qn_{total} \leq 6\%$ 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 tabs not 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 for floor boots, left unsealed.
28	2	7.5%	Leakage at registers, furnace plenum, and joints. Many make-shift tools, take-off material unknown
51	1	8.0%	Leakage at registers, furnace plenum, and joints.
25	2	8.3%	No mastic on furnace 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, 14	2	6.4%	Register installed under interior wall (inaccessible for sealing). Mastic applied incorrectly
47	1	6.5%	Tab-over boots not making contact with trunk line. Gaps in mastic application
50	1	6.1%	Leakage found at registers, furnace plenum, and duct joints. Mastic applied inconsistently Poor 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):

- Floors that met the Qn_{Out} but not Qn_{total} (n=14). Qn_{total} range: 6.1% to 9.7%
- Floors that met the Qn_{total} but not Qn_{Out} goal (n=1) Qn_{Out}=4.1%
- Floors that met neither goal (n=7).

Six of the 7 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 $Qn_{total} \leq 6\%$.

Table 8 Mastic Sealed Systems Exceeding Target Leakage Rates			
ID#	**Floors**	**Qn_{total}**	**Qn_{Out}**
Floors that met the Qn_{Out} but not Qn_{total} (n=14).			
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)
Floors that met the Qn_{total} but not Qn_{Out} goal (n=1)			
67B	1	6.0% (P)	4.1% (F)
Floors that met neither goal (n=7).			
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)

Only leakage to the outside was measured in 7 mastic sealed systems. One floor had leakage too low to measure. All six remaining floors failed to meet the Qn_{out} goal (Table 9.)

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 by researchers as a "machete" 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.

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, 2003).

Field measurements in new site built homes (Cummings, et al, 2002.) 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 field data, MHRA used 50% as the multiplier to estimate Qn_{Out} from the measured Qn_{total} (MHRA, 2003.) 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.

BAIHP data includes 26 taped systems that researchers tested for both total and outside leakage. The average ratio of outside 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 $Qn_{out} \leq 3\%$ goal without meeting the $Qn_{total} \leq 6\%$ goal.

This lower than expected ratio is perhaps due to the improved sealing at joints between duct components but not between the house envelope (e.g. subfloor or ceiling) and the air distribution system (e.g. supply boots and return plenums). Leakage where the supply boot joins to the house is part of the total leakage, but tends to be associated with leakage to the interior of the house.

Though the average ratio of outside to total leakage in the mastic sealed systems was slightly lower than expected (36%), the range spanned 0% (leakage to outside too small to register) to 80%. The data strongly supports that achieving a Qn_{total} of 6% signifies that the Qn_{Out} will be less than 3%. One exception was documented (Qn_{Out}=4.1%), proving that using Qn_{total} as a surrogate test for the Qn_{Out} goal is not a guarantee.

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, 2002. MHRA, 2002) to substantially correlate with duct leakage to the outside of completed houses, the factory's ultimate quality goal.

The support of BAIHP as objective, third party experts is often cited by manufacturers 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.

7. Economics of Duct Tightening in Manufactured Housing (see Appendix C)

Costs for implementing tight duct recommendations were recently reported by Bert Kessler, VP Engineering, Palm Harbor Homes; Craig Young, Engineering Manager, Palm Harbor Homes, Florida Division; and Michael Wade, Director of Quality Assurance & Code Conformance, Southern Energy Homes.

Correspondence from Bert Kessler, VP Engineering, Palm Harbor Homes (Kessler,'03.) (Included in Appendix C.)
Mr. Kessler wrote to BAIHP, "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 50in^2 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 estimates total cost for materials and labor = $7.66 per floor

Kessler notes that all duct systems manufactured by Palm Harbor Homes are pressure tested 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 as well as previous production standards, impact the incremental implementation cost. This is illustrated in the following information from Craig Young of Palm Harbor's Florida Division who reports lower labor costs but higher material costs that Mr. Kessler reports for the company at large.

Correspondence from Craig Young, Engineering Manager, Palm Harbor Homes, Florida Division (Young, 03.)
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 for mastic is estimated at $1 per floor.

Young estimates total cost for materials and labor is approximately $8 per floor.

Correspondence from Michael Wade, Director of Quality Assurance & Code Conformance, Southern Energy Homes (Wade, 03.) (Included in Appendix C.)
Mr. Wade reported that Southern Energy Homes is projected to produce 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." Mr. Wade is of the opinion that there is no additional installation cost compared to tape. Material costs were stated to be $6 per floor compared to $2 per floor for tape, an incremental cost of $4 per floor.

Wade estimates total cost for materials and labor is $4 per floor.

8. 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, 1991, 1993, 2003), new manufactured homes (Tyson, et al, 1996. MHRA, 2003), and manufactured homes in failure due to moisture and air flow control issues (Moyer, et al, 2001).

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. The data set is described in Table 10. Taped (58) and mastic sealed (132) duct systems are included.

Table 10 Characteristics of Data Set

	Taped	**Mastic**	**Total**
Factories Visited			24
Total Visits			39
Manufacturers			6
Number of Tests			
Total Sections	58	132	190
CFM25Total Tests	56	124	180
$CFM25_{Out}$ Tests	30	86	136
Sections Tested CFM25Total and $CFM25_{Out}$	26	80	106
Duct System Location			
Undocumented Location	1	0	1
Overhead Systems	25	44	69
Floor Systems	32	88	120
Total	58	132	190
Duct Materials			
Undocumented	5	0	5
Sheet Metal with Flex	24	22	46
Duct Board with Flex	29	110	139

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 $Qn_{total} \leq 6\%$ and $Qn_{out} \leq 3\%$. Only one system achieved $Qn_{total} \leq 6\%$ but not Qn_{Out}<=3%. This exception had a Qn_{out}=4.1%. An additional 14 mastic sealed systems met the $Qn_{out} \leq 3\%$ with a Qn_{total} >6%, exceeding the total leakage goal.

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 $Qn_{total} \leq 6\%$ goal still met the $Qn_{out} \leq 3\%$ 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 $Qn_{total} \leq 6\%$ and/or the $Qn_{out} \leq 3\%$ goals they set.

<u>Summary of BAIHP Approach to Achieving Tight Ducts in Manufactured Housing:</u>

- Set goal with factory management of achieving Qn_{Out}<=3% using Qn_{Total}<=6% as a surrogate measurement while houses are in production.
- Evaluate current practice by testing a random sample of units
- Report Qn_{Total} and Qn_{Out} findings; make recommendations for reaching goals
- Assist with implementation and problem solving as needed
- Evaluate results and make further recommendations until goal is met
- Assist with development of quality control procedures to ensure continued success

Finally, duct tightness goals can be achieved with minimal added cost. Reported costs range from $4 to $8, including in-plant quality control procedures (testing) critical to meeting duct tightness goals.

Achieving duct tightness goals provides benefits to multiple stakeholders. Improving duct tightness diminishes uncontrolled air (and moisture) flow, including infiltration of outside air, loss of conditioned air from supply ducts, and introduction of outside air into the mechanical system. Uncontrolled air flow is an invisible and damaging force that can affect the durability of houses, efficiency and life of mechanical equipment, and sometimes occupant health. With improved duct tightness, manufacturers enjoy reduced service claims and higher customer satisfaction, while homeowners pay lower utility bills, breathe cleaner air, and have reduced home maintenance.

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

Factory 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 Homes
Austin Plant 5	May 2003	Palm Harbor Homes
Austin Plant 7	February 2000	Palm Harbor Homes
Boaz (AL)	April 2000	Palm Harbor Homes
Buda (TX)	May 2003	Palm Harbor Homes
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

Appendix A

<u>Examination of Single Factory's Progress</u>

Appendix A: Examination of Single Factory's Progress

A review of progress at a single factory gives a sense of the process of improving duct systems. Data and observations here are from a factory visited in February, April, and July of 2000. Initially, the duct systems were at Qn_{total}=10%.

The factory managers set out to achieve the $Qn_{total} \leq 6\%$ goal, in preparation for building homes under the EPA Energy Star Program for Manufactured Housing. The managers and staff reached the goal by the third visit.

February 2000

The initial visit revealed that the factory was already using mastic. Two randomly selected sections were tested. Floor 1, a floor system, measured a Qn_{total}=10% falling short of the tightness goal. Floor 2, an overhead system, measured a Qn_{total}=5% meeting the goal.

Several problems with floor system assembly were observed and brought to the managers' attention in a trip report. These 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 tools
- Strap tightening tools (for flex duct zip ties)
- Improve placement of trunk ducts under riser holes precut in the sub-floor,
- Templates for cutting holes in the trunk duct to improve dimensional matching with the risers
- Increasing the size of the bead of mastic applied to joints.

April 2000

The second visit was to evaluate progress in implementing the recommendations made and achieving the goal of duct tightness, $Qn_{total} \leq 6\%$.

No ceiling systems were tested based on the performance found during the first visit and observation that all recommendations for overhead systems in the Trip Report had been implemented.

Observation of the floor system assembly found that alignment had improved, however, other issues were still unresolved:

- Holes for cross over collars and floor risers were still being cut free hand, leading to a host of assembly difficulties. For example, trunk duct holes were being cut too large, making riser attachment difficult and sometimes impossible.
- Workers were confused about where to seal the furnace plenum
- Not all the duct joints were being sealed
- Some joints were not getting adequate mastic

These improvements and remaining challenges were reflected in test results. Researchers tested two randomly selected sections with floor systems. Floor 1 measured a Qn_{total}=7%, down from 10% but just shy of the 6% goal. Floor 2 proved even closer to the goal at Qn_{total}=6.3%.

Recommendations reemphasizing the need to address these observed issues were detailed in a Trip Report.

July 2000
The third visit to the factory found substantial improvement to the floor duct system which was reflected in the test results. Three randomly selected houses were tested:

House 1
Floor 1 $CFM25_{total}$=45 (AHU side)
Floor 2 $CFM25_{total}$=27 (non-AHU side)
Combined $CFM25_{total}$=72
Combined Qn_{total}=5.4%

House 2
Floor 1 $CFM25_{total}$= 43(AHU side)
Floor 2 $CFM25_{total}$= 30(non-AHU side)
Combined $CFM25_{total}$=73
Combined Qn_{total}=4%

House 3
Floor 1 $CFM25_{total}$= 46(AHU side)
Floor 2 $CFM25_{total}$= 16(non-AHU side)
Combined $CFM25_{total}$=62
Combined Qn_{total}=3.8%

All three houses met the $Qn_{total} \leq 6\%$ goal after the recommendations for assembly improvement were implemented. This factory's experience echoes that of other factories that BAIHP has worked with.

Appendix B

Duct Leakage and House Pressure Concepts

Appendix B: Duct Leakage and House Pressure Concepts

In their most basic configuration, forced air central heating and cooling systems circulate air through a distribution system that includes a return duct, an air handler, and a supply duct network. Conditioned air from the house is drawn into the return duct by a fan in the air handler. The fan pushes the conditioned return air over a heating or cooling coil in the air handler. After passing over the coil, air flows through supply ducts to the various supply registers throughout the house where it reenters the conditioned space.

Ideally, the same amount of conditioned air is removed from the house (via the return duct) that is put back in the house (via the supply ducts): volume of return air should be equal to the volume of the supply air. When there is an imbalance, a positive or negative pressure with respect to the outdoors will result. This is true for individual rooms also. If more air is being supplied to a room than is being removed, a positive air pressure (with respect to adjacent spaces, such as the main body of the house) will result. Vice versa, if more air is being removed from a room than is being supplied, a negative pressure (with respect to adjacent spaces) will result.

Extra energy is used to condition outside air in both situations. When rooms or whole houses are pressurized or depressurized, air will move through small cracks and holes to equalize the air pressure. A pressurized room is like a balloon with a small hole. Air is pressing out all sides and seeping through even the smallest break in the air barrier. In a house, this might mean that warm moist air is being pushed into the exterior wall cavity, toward the cold backside of the exterior wall finish. A depressurized room will pull air in from outside bringing outside air in contact with the backside of interior finishes. The resulting conditions may support mold growth, condensation, rot, or material wetting. Thus, the implications of duct leakage range from energy efficiency, to health, durability, and safety.

Air Distribution System Components and Joints

In a 2002 study conducted by the Florida Solar Energy Center, 69 new, installed air handler cabinets were tested and found to have an average leakage of 20.4 cfm when under a 25 pascal pressure difference (Q_{25}, similar to CFM25). This includes return and supply side leaks. Average leakage at the joint between the air handler and supply plenum was 1.6 cfm Q_{25} and at the joint between the air handler and the return plenum was 3.9 cfm Q_{25}. These numbers pale in comparison to the leakage measured in the 20 full duct systems tested: average $Q_{25,Supply}$ of 53 cfm, $Q_{25,Return}$ of 134 cfm, for a $Q_{25Total}$ 187 (Cummings, et al, 2002).

In these 20 homes, the full duct system leakage exceeds the air handler leakage (including plenum connections) an average of 13 to 1. Also note that the return duct leakage exceeded supply duct leakage 3 to 1.

Though ducts and plenums are made of continuous, virtually leak free materials such as foil backed duct board, sheet metal, and sleeved flex duct, they consistently leak. Though flex duct is vulnerable to puncturing, this can not explain the tremendous leakage occurring in even new duct systems. The explanation lies in the fabrication joints and the connections between components.

Joints between ducts are part of the air barrier and have historically been sealed with duct tapes. UL 181 approved tapes are still in use today. An alternative method of sealing duct joints combines the tensile strength of fiberglass mesh and the elasticity of mastic. The seal created by mesh and mastic enjoys a more durable, longer life than the seal formed by tape.

Primary Leakage Points

Most new homes have a single central return with a return grill or a simple return system with far fewer inlets than supply registers. Supply registers are commonly scattered throughout the house to spread conditioned air evenly through the space. Between the return grill and the supply register, there are a multitude of joints and connections presenting possible leakage sites. The following list of common duct system joints combines elements of different types of systems and materials common in the manufactured housing industry:

Ceiling Systems

Return grill to dry wall (sheet metal/duct board)
Return grill to return plenum (sheet metal/duct board)
Return plenum (sheet metal/duct board) to air handler or drop out to package unit
Air handler cabinet joints
Supply plenum (sheet metal/duct board) to air handler
Supply plenum (sheet metal/duct board) to main trunk line(s) (flex)
Main trunk lines to flex collars
Flex collars to supply ducts, both ends (flex)
Flex collar to supply boot (duct board)
Supply boot to drywall
Supply boot to supply register
Supply register to drywall

Floor Systems

Return grill to dry wall
Return grill to return plenum (sheet metal/duct board)
Return plenum (sheet metal/duct board) to air handler
Air handler cabinet joints
Supply plenum (sheet metal/duct board) to air handler
Supply plenum (sheet metal/duct board) to main supply trunk line(s) (sheet metal/duct board)
Main trunk line(s) (sheet metal/duct board) to floor riser or collar
Floor riser (sheet metal) to sub-floor (In-line floor system)
Collar to branch duct (sheet metal/flex) (Perimeter floor system)
Branch duct (flex/sheet metal) to collar
Collar to floor riser/supply boot (sheet metal)
Riser/supply boot (sheet metal) to subfloor

In addition to these joints, all the surfaces of all the components in the air distribution path should be free of holes, tears, cracks, punctures, gaps, etc. This includes the fabrication seams in the components. The entire inside of the duct system from the return air inlet to each supply air outlet* should be an air tight, planned air flow path.

A note about return air paths

An additional factor contributing to unbalanced house pressures include inadequate return air paths from bedrooms. This creates positive pressure in the bedrooms when the bedroom door is closed and air is trapped. At the same time, a negative pressure results in the main body of the house as the air handler continues to draw the same amount of return air from the open part of the house. Thus infiltration is induced in the main body, while exfiltration is induced in the closed room(s). Though this is not a direct result of duct leakage, it is a result of having a central return rather than a ducted return from each private room. Methods of overcoming the limitation of return air from bedrooms include providing ducted passive return paths (jump ducts or saddle ducts) or through wall passages (high-low vent or over door) for return air to move from bedrooms to the air handler. In diagnostic testing, BAIHP has documented the impact of this phenomenon on house pressure, resulting in recommendation to balance supply and return air into private rooms using passive devices such as through wall/door grills, high-low wall grills, jump ducts (also called saddle ducts), or individual return grills ducted to a central return plenum.

References

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.

**All outside air inlets should be air tight from the outside air intake grill to the mixing box and should be equipped with air tight, automatic dampers with a manual override switch.*

Appendix C

Letters from Manufacturers Regarding Cost

Palm Harbor Homes

July 30, 2003

Dr. Subrato Chandra
Director
Building America Industrialized Housing Partnership (BAIHP)
Florida Solar Energy Center
Cocoa Beach, FL

Subject: Duct testing and Return Air Improvement Costs

Dear Subrato:

Per our discussions, the following is an average cost per home for our entire product line as it relates to the procedures and measures we implemented company wide, to improve duct tightness and conditioned space pressure imbalances. As I mentioned before, the costs vary significantly from plant to plant, based on where duct blaster tests are performed, what type(s) of duct system a particular plant is using, and how return air requirements are handled.

Based on the research we did over the years with your staff under the BAIHP program, we implemented both duct blaster testing and increased return air requirements as part of our standard procedures, throughout all facilities, regardless of whether home is designed for Energy Star® or not. These requirements were incorporated into our DAPIA approved design manual, and as such, are subject to third party inspections on a regular basis, the same as all other aspects of the DAPIA approved design.

The benefits of these requirements far exceed the cost, both to the consumer and the manufacturing facility. In fact, since implementation of these requirements in February 2000, we have had no incidents of moisture related issues for homes installed in the hot and humid climates of the south. Additionally, airflow related issues have been all but eliminated.
To-date, we have built approximately 35000 homes with these features, resulting in huge energy savings and increase of comfort levels for our customers, not to mention reduced service costs for our facilities.

The requirements are as follows:

1. Duct Testing: the HVAC duct systems for each home are tested to a target cfm loss of less than 3% of floor area @ 25 pascals pressure. Example: for a 14x76 section @ 1039 ft^2, the maximum CFM25 duct leakage would be 1039x0.03= 31cfm.

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Building a Legend

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2. Return Air: Return air requirements are based on the amount of cfm's delivered into the space. Since PH does Manual "J" room-by-room calculations, we know how many cfm's go into each space by design. Return air requirements are based on minimum $50in^2$ for every 100 cfm's delivered into that space. As you well know, the FMHCSS require return air be based on $1in^2$ for every $5ft^2$ of area in that space.
3. Duct Sealing: All duct connections to register boots, furnace plenum and branch ducts are sealed with Mastic. Duct tape is not allowed.

Based on these requirements, the following costs are incurred, assuming a typical 28x76, $2026ft^2$, 3-bedroom unit:

Duct Blaster equipment: This is a one-time expense except for maintenance and calibrations.	S1650.00	
Mastic for heat ducts (replacing tape):		S2.90
Additional/larger grilles over doors:		S7.56
Added lumber for grill frames:		$1.24
Additional in-ceiling grilles as required:		$14.36
Marriage line Gasket:		$28.00
Total material cost:		S53.16

It must be noted that the marriage line gasket was already a standard application when duct blaster testing and increased return air requirements were implemented. The total cost as shown, therefore, reflects the anticipated industry average.

Estimated Labor costs:

Labor is estimated @ S14/hr x 1.33 for benefits or $18.62/hr.

Marriage line gasket installation:	20min	S6.21
Duct testing, 2-people, 20 min/section	40min	S12.42
Add'l grill installation, 30min/section	30min	S9.31
Total Labor cost:		$27.94
Total material and labor (avg. manufacturer):		S81.10

Actual labor increase to Palm Harbor was only S9.31 as gasket and duct testing procedures were already in place prior to implementation of the duct blaster and return air requirements. The total average cost for PHH is around S35.00.

Again, the actual costs per individual PH plant vary due to existing procedures, type of duct systems (floor, ceiling, or both), and location during production where duct testing is performed.

In addition to the testing of the duct systems at the production facilities, several of our divisions have purchased additional duct-blaster equipment to evaluate site installations of equipment and duct connections. It is typical in this industry that AC-installers do not check for system balance or air tightness of site installed duct connections.

That, coupled with gross over sizing of equipment, results in many unnecessary consumer complaints. As you are well aware, Palm Harbor actually recommends the optimum AC-tonnage for each home we sell, based on the geographical design conditions of the final site. I know of at least three recent occasions where the consumer complained about improper cooling of the home, only to be told by the AC contractor that the unit was too small. Our service department performed a duct blaster test and discovered huge leaks at the cross over duct connections. Once repaired, the home cooled down just fine.

As you can see, the results of your team's research and recommendations reach beyond the production environment, at least as far as Palm Harbor is concerned.

We certainly appreciate your continued cooperation.
Should you have any questions, feel free to contact me.

Bert M. Kessler
Vice President, Engineering

Southern Energy Homes, Inc.
P. O. Box 390
Addison, Alabama 35540

5-30-03

Subrato Chandra, Ph.D., P.E.
Florida Solar Energy Center
1679 Clearlake, Road
Cocoa, FL 32922

Re: Construction of Manufactured Homes to be placed in hot and humid climates

Dear Mr. Chandra,

Southern Energy Homes, Inc. has experienced nothing but positive results from working with the team at FSEC and by participating in the Building America Industrialized Housing Partnership. In regards to the added expense of constructing a unit that will be placed in "humid climates" as set forth in the 1989 ASHRAE Handbook of Fundamentals, I would like to share the following breakdown of construction materials/practices:

- Use of duct mastic. This has significantly reduced the amount of measurable duct leakage in our units. We typically use about 3 tubes per floor (at approx. $2.00 per tube) vs one half of a roll of metal tape (at a cost of $4.00 per roll), leaving us with an actual increase of approx. $4.00 per floor.
- Increased return air pathways. We are currently using grills in or above the bedroom doors. The rule of thumb being followed is to provide 50 s.i. of net free return air for every floor/ceiling register that is placed behind a bedroom door. These grills are single sided, so each application requires two grills. We use a 8"x16" (50 s.i.) at a cost of $3.63 each and a 16"x16" at a cost of $7.00 each. A typical house will have three bedrooms (smaller grill used on #2 & #3 bedrooms, while the larger grill is used on the Master).
- Marriage wall gasket. We put a gasket along the floor, endwall and ceiling of the marriage line of each multi-section home (fastened to one section of the home) in an effort to completely seal off the marriage line at the time of installation. The price of this gasket is 18.6 cents per linear foot.
- Balanced air flow. Our Draftsmen use the Certiduct program from Nordyne to evaluate the air flow through the registers prior to construction. Any problems can be corrected by reducing/relocating registers as necessary prior to construction. This program is provided free of charge from Nordyne.
- Louvered door on Utility Room. When the air handler is placed in the Utility room, we use a louvered door to increase return airflow. The cost of this door is $85.00.
- Testing with a Duct Blaster. We strive to test the duct system of each floor produced to ensure that we consistently achieve our goal of having less tha

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- n 3% duct leakage from our duct systems. While the initial cost of the Duct Blaster is in the $1, 600.00 range, the test can be performed so quickly that we do not take the labor expense into consideration.

Breakdown of the above for a 76' long unit with 3-bedrooms:

	Per Floor	**Multi-section with two floors**
Mastic	$4.00	$8.00
Return air	$13.00	$26.00
M/W gasket	$15.62	$31.25
Louvered door	$42.50	$85.00 (if used)
Total	$32.62 w/o door $75.12 w/door	$65.25 w/o door $150.25 w/door

Cost of Duct Blaster not factored in due to variance in production rate and no specific time period of floors produced to spread the cost over.

I hope that this information is beneficial to your team and to whomever else you choose to share it with.

Sincerely,

Michael Wade
Director of Quality Assurance & Code Conformance