APPENDICES

A

INDIVIDUAL PLANT REPORTS

Duct leakage measurements for all plant reports are expressed as the number of cubic feet per minute of air leaking from the ducts (either total leakage or leakage to the outside) when they are pressurized to 25 pascals, divided by the overall square footage of the home, given as a percentage.

For example: 30 cubic feet per minute divided by 1,150 square foot floor area equals an estimated leakage of 2.6%.

Where the plant reports state a percentage leakage figure, these units are implied.

PLANT 1

Summary

The factory uses a fiberglass duct board trunk system with side-mounted branch takeoffs and R-4.2 flex duct branch connectors attached to standard floor boots. Initial duct leakage was measured at 138 CFM25, corresponding to a duct leakage of 21% cfm/ft^2 (~11% to the outside). After instruction from the building scientist and cross-training with staff from a sister plant, duct leakage levels of less than 4% were achieved. Duct leakage levels of less than 5% will be consistently achievable by this plant. Table 1 below demonstrates this with homes testing in the 3.3% to 3.8% leakage range after implementation of ADS improvements.

Test Results

Table 1: Results from duct leakage testing

Test home number	Home area (square feet)		Estimated leakage to the outside
1	1650		3.5%
2	1248		3.3%
3	1633		3.8%

ADS Efficiency Measures

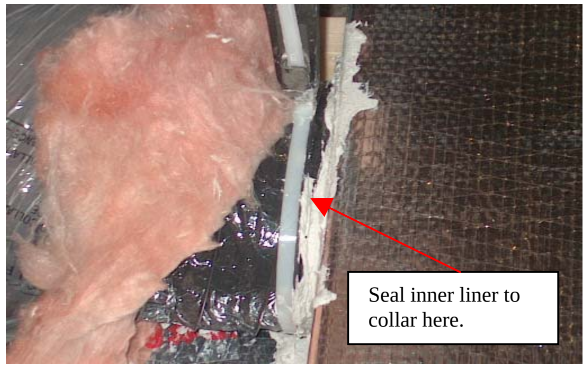
1. **Seal side mounted collars.** Fiberboard systems rely on tabs folded into the duct for mechanical fastening. These are less rigid than screw-type fastenings and increase the difficulty of sealing. Tapes designed for metal to fiberboard attachment may be used for sealing these collars; and some manufacturers have had good success with this method. The other method (practiced at this plant) is to apply enough tape to secure the collar at the top and bottom, and to apply a liberal layer of mastic completely covering the tape.

   The tape will support the duct during construction in the plant and the mastic will eventually cure to form a strong, durable seal. However, curing of the mastic could take several days depending on temperature and humidity conditions.

It is difficult to create a durable seal using tape or mastic alone.

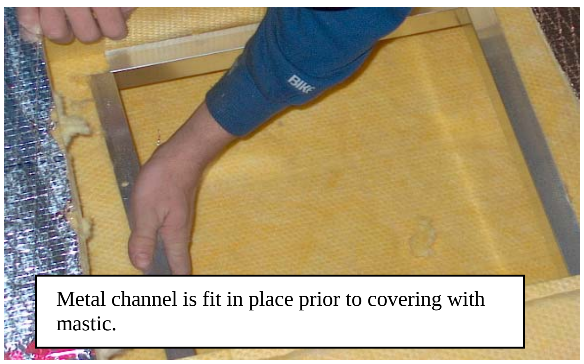
Applying tape as a temporary seal then covering the seam and tape with mastic will result in a superior and durable seal.

2. **Secure and seal the flex duct to the side-mount collars.** The inner liner of the flex duct should be fastened and sealed. Tape may work in this location if a plastic strap is used over it; otherwise mastic makes a good seal here as well. The inner liner should first be placed on the collar and attached with a plastic strap to hold the liner in place.



Seal inner liner to collar here.

3. **Use care and attention to detail in crossover branch connections**. This is a critical area for leak prevention. Apply a good quantity of mastic between the mating surfaces of each trunk. Accurately cut the holes and use the metallic channel material shown to serve as a mechanical attachment. This material should be sealed with mastic along all exposed edges. Strap the two trunks securely to prevent any movement of the duct until the applied mastic has had sufficient time to cure. Installers should be made aware that the mating surfaces are relatively fragile and may open if any pressure is applied to either trunk prior to curing.



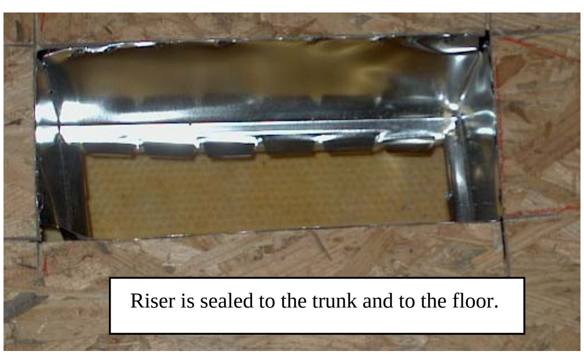
Metal channel is fit in place prior to covering with mastic.

Trunk-to-trunk connections are subject to damage during construction. Take care not to disturb.

4. **Seal in-line boots to the trunk and to the floor.** Apply mastic to in-line risers prior to installation with a caulk gun. Steps are: Cut a properly sized hole into the trunk, apply mastic, install riser, and fold up tabs to complete the sealing. Other risers are available that are easier to seal (less prone to being messy).

   All openings between the boot and the floor should be sealed. These small holes can add up to significant leakage.

Applying mastic to riser prior to installation. This riser style has a “hip” for mastic and is less messy than finger tabs.



Riser is sealed to the trunk and to the floor.

Many small holes can add up to significant duct leakage.

Perimeter supplies need to be sealed to the floor to prevent leakage into the belly.

5. **Redesign the furnace plate/plenum to the duct board connection**. The furnace connection is often the leakiest site in the duct system. One option is to manufacture a metal channel designed to attach the inside of the duct board material and the plenum sidewall. The channel should be secured with screws and sealed with mastic.

   Other manufacturers are having success using liberal amounts of mastic applied by gloved hand to the folded finger tabs of the existing furnace plate.

Furnace plate prior to sealing to trunk with mastic.

Furnace plate after sealing to trunk with mastic.

6. **Use care and attention to detail in the crossover connection termination at the rim joist.** At the plant, the crossover is accomplished by extending a 6" flex connector through the marriage wall band joist in multiple locations. The connection between opposite halves of the home is done by the installer. This design leaves the essential duct sealing task to the installation crew. A faulty connection will directly impact ASD leakage.

Multiple through-the-rim 6” flex duct crossovers to be connected during home set up.

PLANT 2

Summary

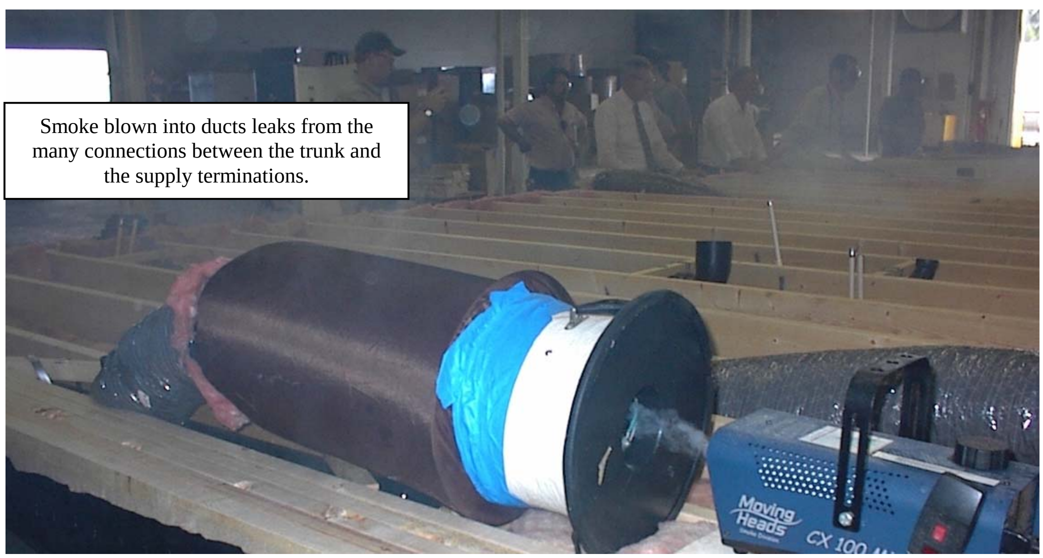
This plant produces double-section homes using 6-inch stud wall construction, cathedral ceilings, OSB sheathing for end-walls, and foam core sheathing for side-walls. Space conditioning is normally provided by a downdraft gas furnace. Conditioned air is distributed using a single graduated fiberboard trunk duct located on the furnace side with supply terminations on both sides of the home connected to the trunk with flexible duct. The use of a single trunk requires multiple crossovers of flexible duct under the marriage line to supply the "non-trunk" section.

Homes tested for this report were representative of models typically produced in this plant. Ducts were inspected and tested from floors in the production line and in a set-up home on the manufacturer's grounds. The results showed a range of duct leakage rates between 2.5% and 9% compared to the selected target leakage of 5%. A smoke test of the ducts showed leakage from many of the connections.

Test Results

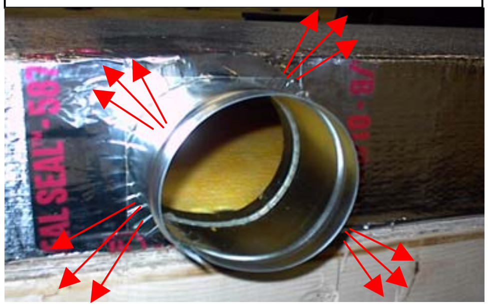
Table 1: Results from duct leakage testing

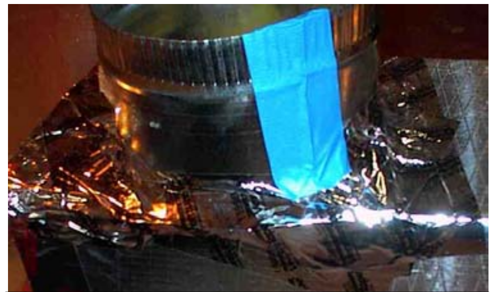
Test home number	Home area (square feet)	Estimated leakage to the outside
1	1,502	1.7%
2	1,392	2.2%
3	1,392	2.3%



Smoke blown into ducts leaks from the many connections between the trunk and the supply terminations.

Smoke is seen leaking under the collar flange.





Round collars completely sealed with tape (above) or mastic (below) show no leakage.

ADS Efficiency Measures

1. **Seal start collars to trunk**. Start collars are known to leak, especially when freehand cut "round" holes are used. Use mastic or 100% tape coverage to seal start collars to the fiberboard.

2. **Seal flex duct to metal collars and boots with tape**. Straps alone will not seal flex duct to metal. Use appropriate tape to make this seal. Use tape and straps in conjunction with the multiple crossover connections.

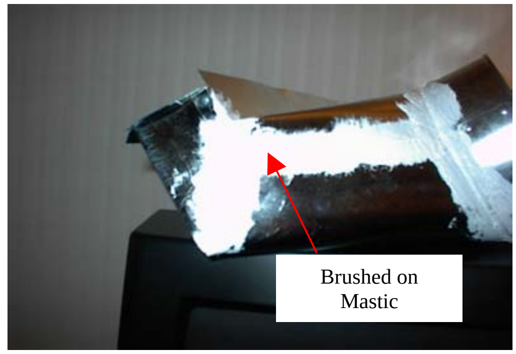
Step 1: Tape inner liner to start collar.

Step 2: Secure inner liner with strap.

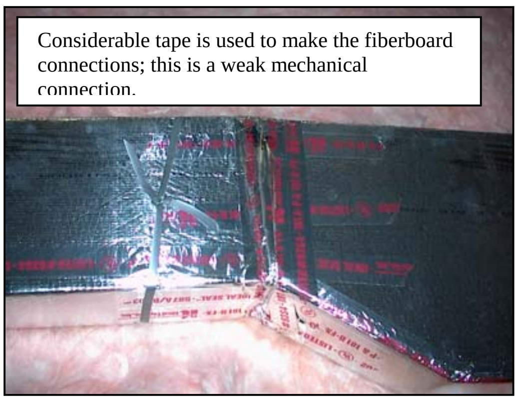
Step 3: Seal start collar with mastic.

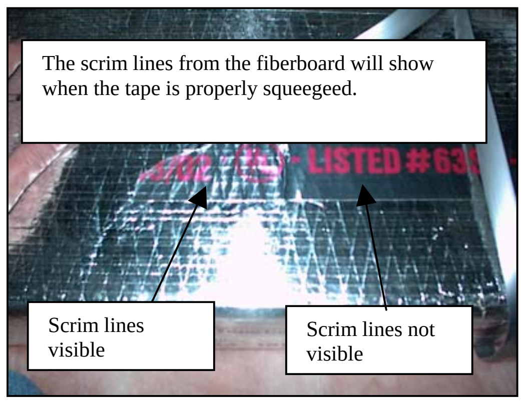
Step 4: Bring outer liner up and strap it.

3. **Seal boots with mastic**. Supply boots have gaps that will leak conditioned air into the floor system, which in turn can leak to the outside. Because there are six or more in each section, this can add up to significant leakage. Cover all the seams completely with tape or brushed-on mastic.



4. **Use a squeegee tool on taped joints in fiberboard ducts.** Moderate stress is applied to the trunk when it is moved from the overhead station where it is assembled to the floor below. Be sure taped seams are properly squeegeed to ensure maximum adhesion strength. Take care not to break any seams when moving and installing this duct into the floor.

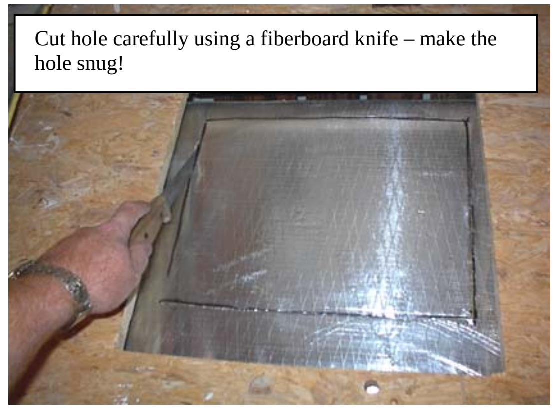




5. **Positioning of the trunk is important for a proper seal with the air handler**. The furnace plate connection is the most important connection to seal. In several homes the trunk was not secured snuggly to the floor joists resulting in a gap between the trunk opening and the furnace plate. Also, trunks were found that were not aligned exactly under the air handler. These are difficult repairs to make leak free. To minimize these incidents, develop an engineered plan for these situations rather than having the production staff make one up on the fly.

6. **Properly fasten and seal the air handler plate to the duct board**. This requires carefully marking the duct board using the furnace plate as a guide and carefully cutting the hole into the trunk. The manufacturer recommends using a duct board knife to make this cut. <u>This hole should not be oversized;</u> there is only 1/4 of lip available for sealing to the duct board. Tape will not seal the plate to duct board. Use mastic as shown.


Use appropriate depth plate. Mark fiberboard carefully.


Cut hole carefully using a fiberboard knife – make the hole snug!


Apply generous amount of mastic or other sealant to the hip of the furnace plate


Fold tabs into fiberboard duct and check for firm fit.

Additional mastic can be used to fill any remaining gaps in this connection. Mastic should not be used as a substitute for a poorly made cut. Mastic will not provide structural support – only air sealing. Mastic should be allowed to fully cure before use.

7. **For improved airflow, minimize excess length and curves in the flexible duct sections.**

PLANT 3

Summary

This plant uses a perimeter duct system with fiberboard trunk ducts (5-3/8” x 13-3/8”) and flexible supply ducts (2” x 12”). Crossover ducts are 3” x 13”. Results from the testing are summarized in the Table below. Only two units were available for testing. Both units easily met the 3% leakage to the outside target.

Test Results

Table 1: Results from duct leakage testing

Test home number	Home area (square feet)	Estimated leakage to the outside
1	1,728	<1.0%
2	1,538	<1.0%

ADS Efficiency Measures

Provided duct leakage testing orientation

- Provided instruction on how to use the duct blaster during two field tests (plant set ups)
- Illustrated common problem areas affecting duct tightness
- Provided guidance to minimize measurement error when pressure testing
- Provided guidance during duct leakage testing

PLANT 4

Summary

Four floors were tested in the plant to measure total duct leakage. The results from measured leakage are as shown in Table 1. All homes met the preferred duct leakage rate of 3%. Leakage to outside and total duct leakage were measured on one single section home. In this home 24% of the total leakage was attributable to the outside.

Test Results

Table 1: Results from duct leakage testing[1]

Test home number	Estimated leakage to the outside
1	~1.0%
2	~1.0%
3	~1.5%
4	~1.0%

ADS Efficiency measures

Below is an interior view of the marriage wall which shows the plant-installed marriage line gasket and the through-the-rim crossover duct.

[1] All homes have through-the-rim crossovers with substantial gaskets. It is anticipated that the crossover will add very little to the duct leakage.

Close up of crossover configuration. Note the use of mastic to air seal the trunk prior to the application of the gasket.

DAPIA installing calibrated duct fan at the preferred location to measure duct leakage. Removing the blower and measuring close to the ducts minimizes measurement errors.

DAPIA installing calibrated fan at a supply to measure duct leakage in a floor section that is without a furnace. Although this is a less preferred location to access the ducts, with the small leakage levels experienced, any error is negligible.

PLANT 5

Summary

Duct leakage was measured in three homes. The plant had engaged in air distribution sealing activities prior to this visit and was already using mastic for sealing. The total duct leakage measured 5% (estimated leakage to the outside of 2.5%). After completing training the total duct leakage was lowered to less than 1.5%. The current duct sealing practice will satisfy 5% leakage to the outside set as the project target with no further efforts. The current practice is likely achieve 3% leakage to the outside, however, some additional suggestions are presented here which will help the plant improve consistency and achieve a higher margin of safety in attaining this value.

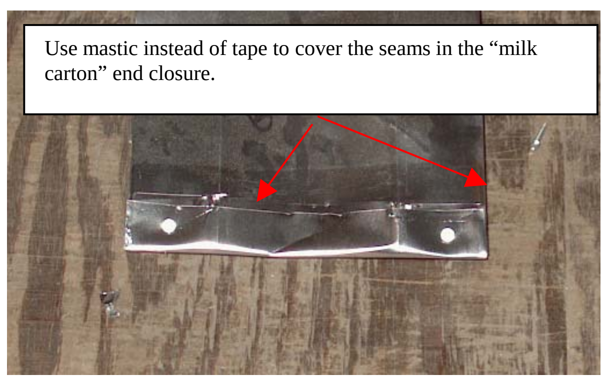
Test Results

Table 1: Results from duct leakage testing

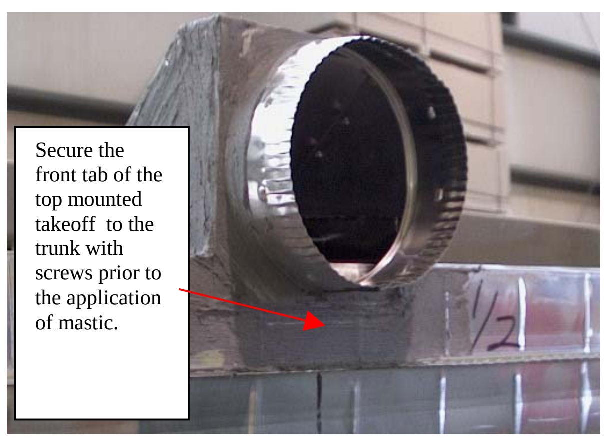
Test home number	Home area (square feet)	Total leakage in the plant	Total leakage in the field	Leakage to the outside (of set-up home)
1	2,027	1.5%	4.2%	1.1%
2	2,027	1.8%	5.1%	1.1%
3	2,027	1.3%	5.0%	1.4%

ADS Efficiency Measures

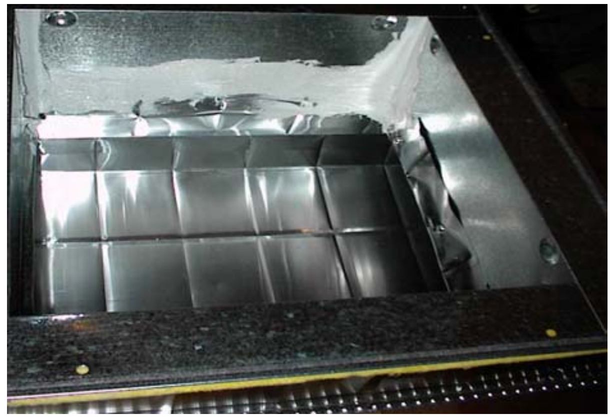
1. **Use brush on mastic along the seams in the end closure.**
   The trunk ends were capped by folding the end over. The technique was tested and found to be airtight, however, in other plants this technique has been shown to leak at the seams. Careful attention should be paid to preserve the integrity of the seams when folding the trunk.



2. **Consider improving the top mount connection**
   Top mounted trunk takeoff connections being used are a good choice for air sealing. A more secure attachment to the trunk can be achieved by fastening the front tab onto the front of the trunk with screws prior to the application of mastic to all seams.



3. **Redesign furnace plate seal**.
   There is often little tolerance for locating the furnace base over the trunk. This is the worst leak site in the duct system. MHRA recommends making a "picture frame cut" into the trunk, screwing it into the furnace base and sealing with mastic. This will result in a more airtight and durable connection. (See the MHRA publication Duct Systems: Guide to best practices Figure 5.4 for a good illustration.) The furnace manufacturer should review this recommendation.



4. **Make picture frame connections in branch connections.**
   When making branch connections between two metal trunk sections, make a "picture frame"-shaped cut into the lower trunk and fold the bottom trunk flaps into the top trunk. This will result in a more air-tight connection. Screws should be used to provide the mechanical connection prior to applying mastic on the exposed seams.

PLANT 6

Summary

Two duct systems were tested that had been sealed using foil tape, the current plant practice. The first system tested was in a floor in the plant and the second system was in a completed single section home. These ducts showed total leakage of 9.2% (72 CFM25, total) and 8.4% (68 CFM25, total) respectively. The single section home was also tested for duct leakage to the outside. The results showed that 40 CFM25 outside or 60% of the duct system total leakage was to the outside.

Following the training of plant personnel, three more floors were tested in the plant to measure total duct leakage. Mastic was used in place of the foil tape. The resulting leakage rates are shown in Table 1 and represent a significant reduction in total duct leakage to the outside.

Test Results

Table 1: Results from duct leakage testing of four floors sealed with mastic

Test home number	Home area (square feet)	Estimated leakage to the outside
1	950	~1.8%
2	1,150	~1.0%
3	1,000	~1.1%
4	1,150	~2.6%

These homes are projected to meet the 3% target for duct leakage when properly set up in the field.

ADS Efficiency Measures

Blower door testing being conducted in a single section home outside the plant.

Duct tightness testing in the plant. This home section has no air handler unit so testing equipment is connected to a supply opening.

Duct tightness testing in the plant. Testing equipment is connected to the furnace plate before the air handler is installed.

Training plant personnel on the proper application of mastic to the duct system.

Furnace plate sealed with mastic.

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PLANT 7

Summary

Three floors were tested where the ducts had been sealed with mastic. These three floors met the 3% duct leakage target, averaging 1.7% leakage to the outside.

Test Results

Table 1: Results from duct leakage testing

Test Home	Home area (square feet)	Estimated leakage to the outside[2]
1	1,590	2.3%
2	1,590	2.1%
3	1,590	2.2%

ADS Efficiency Measures

The duct system used was a standard in-floor rectangular shape residential-type fiberglass, fabricated in the facility from flat stock. Trunk ends and butt joints were secured with UL approved sealing tape. Aluminum supply risers and furnace connectors were installed to the main trunk after the trunk was secured to the floor and the floor attached to the chassis. Flexible circular insulated ducts were used in some locations to provide supply air to the perimeter area of the home. These flexible ducts, and their metal connectors to the trunk duct, were installed before the floor was secured to the chassis.

This facility uses a "loop" type duct system which incorporates two crossover points, one near each end of the floor, for double-wide homes. The crossovers are an in-floor type. The perimeter rim joist is notched and shimmed to allow space for the crossover. The face of one perimeter joist, around the perimeter of the crossover duct, is surfaced with two one-inch wide strips of fiberglass duct material to serve as a gasket when the two floors are mated in the field. Also, a sheet-metal insert sleeve approximately 18" long and sized to the inside dimensions of the duct is shipped with the home for installation into the crossover when the floors are mated. Personnel indicated there had been problems and complaints associated with the sheet-metal insert in the field. The building scientist noted that on some floors online, it was impossible to install the insert into the crossover. This problem was determined to be caused by under-sizing the hole in the rim joist, thus squeezing the crossover duct down where it entered the rim joist.

A mock-up of the crossover was built to measure leakage at that point. This was done for two reasons; f to evaluate the crossover for leakage since no mated double-section homes were available for duct leakage testing, and second, to evaluate an alternative crossover design. The mockup was built using two 30"-long pieces of 2x10, with a hole cut in each piece to accommodate two short 30" sections of crossover duct with the ends capped and sealed. The existing crossover design (metal insert sleeve and fiberglass gaskets) was tested and found to be virtually air-tight. Next, a new configuration was fabricated and tested. This configuration did not use a metal insert sleeve. The crossover ducts were stapled to the 2x edge of the hole in the simulated rim joist member using two wide-crown staples into both long dimensions of the crossover (total of 4 staples per crossover duct). Mastic was applied to seal each crossover duct to the back of the rim joist, and one inch "P"-shaped

[2] This estimate assumes that 50% of total duct leakage will manifest as leakage to the outside.

foam gasket material (same as used to seal the mating line) was applied to one rim joist only and used to seal at the rim joist mating surfaces. Test of this new design was also found to be essentially air-tight. The new design was deemed to represent a cost saving in material and labor and also be easier to use in the field.

PLANT 8

Summary

Four floors were tested. The average total leakage was less than 30 CFM25. These tests indicate excellent duct tightness. With proper crossover connections, these homes will exceed the duct leakage tightness target in the field. While duct leakage to the outside could not be established in the plant, outside leakage on average is about half of the total leakage values. If homes consistently satisfy the duct leakage requirement using *total* leakage values, then it is given that they will also pass the requirements for leakage to the outside.

Test Results

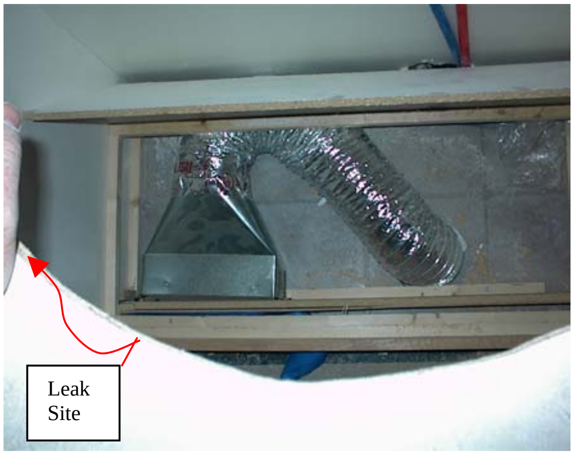
In-plant testing was conducted November 15 and 16, 2001 to measure the total duct leakage in a sample of homes. Tests were conducted using the factory cover of the crossover collar. (The "factory cover" *covers*, but does not *seal*, the crossover collar.) Although anticipated to contribute to the measured leakage, most of these homes still satisfied the targets for duct leakage.

Table 1. Results from duct leakage testing

Test home number	Home area (square feet)	Total leakage	Estimated duct leakage to the outside[3]
1	728	4.4%	2.2%
2	728	4.3%	2.2%
3	938	2.6%	1.3%
4[4]	938	Could not pressurize	Could not pressurize
5	756	3.2%	1.6%
6[5]	756	10.4%	5.2%

Note: The plant puts axles on its homes only near the end of construction. Thus for most of the production process, it is impossible to get under the home to properly seal the crossover collar for leakage testing. This can complicate in-plant duct testing procedures. The tests relied on the flex collar covering, which, although not designed as a seal, in most cases provided adequate sealing for the tests.

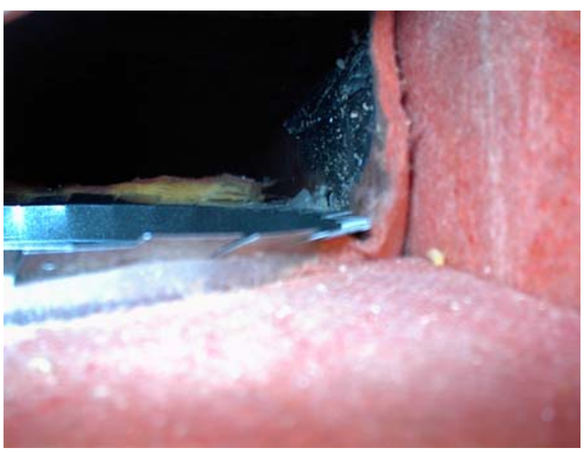
[3] This estimate assumes that 50% of total duct leakage will manifest as leakage to the outside.
[4] Ducts in home # 4 would not pressurize for the test. Remote visual inspection suggests that the crossover was uncovered.
[5] Higher than normal duct system leakage in home #6 was unresolved. However it is obvious from inspection that the crossover flex collar was originally located over a stabilizing bar of the frame and subsequently had been moved. It is likely that either the movement of the flex collar caused some leakage or that when the home was flipped, the fiberboard duct trunk system was partially crushed. Such damage has been observed at other manufacturers employing a similar process.



ADS Efficiency Measures

This is a view looking down through a bathroom sink cabinet to the toe-kick supply. This supply was not mounted flush to the cabinet and the cabinet fascia was cracked. By sealing this supply 14 cfm was added to the total duct leakage measurement. In theory this leak would all be eliminated under leakage to the outside test. To fix the problem, screws were used to mechanically fasten the connection and the duct test was repeated.

Low clearance under the homes in the plant limited the access to the underside of the homes. The status of the belly and crossover collar cannot be confirmed until the end of the construction process when the home is lifted onto axles.



A partial repair of the crossover collar may be the source of unresolved leakage in this duct. Prior to being relocated, the collar was located over a metal stabilizing bar welded to the frame.

PLANT 9

Summary

Opportunities exist for cost effective improvement in the distribution, durability and quality control in the observed air distribution system. This plant uses a metal trunk duct, typically with perimeter supplies and metal tape for sealing. The trunk is constructed offline except for the in-line registers. In-plant duct leakage tests had to be conducted in three sections due to the “off-set” air handler location.

Test Results

A single 1,512 sf home tested in the field measured 550 CFM25 (total duct leakage at a 25 Pascal test pressure) or 36.4%. This extremely high leakage rate was attributed to a flaw in the manufacturing process. After repair, the duct leakage was measured at 76 CFM25 leakage to the outside (5%).

The same installation flaw seen in the field was observed in three of four homes inspected in the plant. Leakage in a completed trunk with five perimeter supplies was measured at 12 CFM25 or less than 2 CFM25 per supply. Duct measurement in a completed home in the lot was made difficult by having no access into the ducts other than the supply outlets. For a 5-in-line, 2-perimeter 1,125 sf section the leakage measured was 64 CFM25 or 5.6%. Since this is total leakage as opposed to leakage to the outside, this leakage rate may be acceptable; however the typical outside leakage from the furnace (previously measured at 40 CFM25) and the crossover connection may degrade performance below acceptable levels when set up in the field.

After the construction defect was corrected, three floors were tested in the plant to measure total duct leakage. The results from measured leakage are as shown in Table 1. The homes did not meet the preferred target for duct leakage of 3% and are expected to barely meet the 5% target.

Table 1: Results from duct leakage testing of three floors[6]

Test home number	Estimated leakage to the outside
1	4.6%
2	3.3%
3	5.0%

Systems using perimeter supplies should be designed with superior durability because these connections are very difficult to isolate and repair. Air leakage test results were acceptable; however, the metal used to seal the ducts has been shown to fail unless the metal surfaces are first cleaned of residual oil. This is currently not being done.

ADS Efficiency Measures

The following deficiencies were noted in the plant and brought to the attention of the plant staff for correction.

1. It was suspected that the in-line supplies were not well sealed. Homes with more in-line supplies had higher measured duct leakage. Examination of several taped supplies also suggests that this could be a source of significant leakage.

[6] Test results are considered conservative as the ducts were tested without crossover connections.

In-line supply connector showing tape at trunk connection. Cutting a properly sized hole and applying mastic to the connector prior to insertion into the floor is the preferred method of insuring a good seal.

2. Furnace connection, distribution box. Secure the crossover duct splitter box to the furnace connector boot with screws when the boots are assembled off line. This is a critical leak area worthy of regular in-plant inspection.

   Redesign the furnace connection box without tabs. Such a redesign may encourage the use of screws which are sometimes being left out. Also be sure the optional plate is removed when it is unnecessary.

   The furnace gasket supplied by the furnace manufacturer seems to be excessively small. Be sure this gasket doesn't leak. Consider a larger gasket.

   The outdoor air ventilation duct is connected directly to the furnace. If this is not changed when the air conditioning A-coil is installed, ventilation air will not receive direct dehumidification which can result in poor humidity control.

3. In-Line Supplies. Use the correct in-line supply riser length to match the joist dimension or cut length to fit.

   Consider a better sealing method than tape which is slow and prone to failure.

   In-line supply risers with a screw down hip are preferable to those with finger tabs.

   Consider converting the in-line risers to short perimeter-type flex duct connections or use wider (4-inch) in-line risers for more accurate positioning.

   Investigate using spiral "zip saw" or other method to cut the trunk for the in-line supply risers and perhaps for cutting the perimeter takeoffs as well. Such a tool will make use of templates more practical.

4. Perimeter supplies. For the perimeter flex duct assembly, use mastic foil tape on the inner liner and a strap and cloth duct tape on the outer liner.

   Redesign the rectangular-to-round flex duct take-offs for the perimeter supplies with wider or single tabs. Larger tabs will leak less often and offer a larger target for screw fastening at this connection.

   Trim the vinyl flooring away from the perimeter supply.

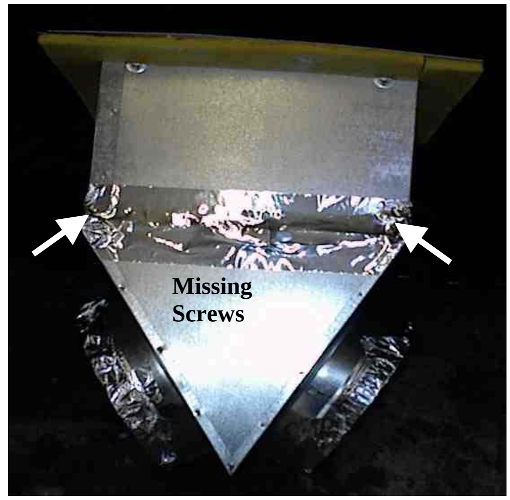
5. General recommendations. A significant portion of the duct leakage may be redirected into the home by sealing the perimeter of the belly material and carefully repairing any penetrations to the bottom board. This may be simpler than many of the other recommendations.

   Clean metal surfaces with a solvent before applying tape for improved durability.

   Investigate why walls often partially cover supply outlets and correct.

Detailed plant observations:

1. The metal "crossover duct splitter box" was not mechanically secured to the "furnace connector boot" in three of four inspected homes. This critical connection was held together with only one layer of foil tape. The crossover duct splitter box could become disconnected from the furnace connector boot due to the weight of the splitter box and crossover duct.. The crossover duct splitter box and furnace connector boot were pre-assembled off line and should have been secured with 4 screws when the furnace was installed. To avoid this oversight, these screws should be installed off line when these duct pieces are first assembled.



2. The in-line supply register risers have several shortcomings:
   The very narrow profile of the connector (less than 3") leaves insufficient room for the hand and arm to reach in, cut the rectangular opening in the supply trunk, install the riser and tape the joint. Installed through the subfloor, these connectors take considerable time to install. Installation of two risers took two men approximately 30 minutes. The resulting connections have four times as much air leakage compared to the perimeter connectors.

   Twelve-inch long connectors being used are too tall for use with the 10" floor joists. The boots extended into the supply trunk blocking airflow and causing duct leakage. As installed, the in-line ducts inspected will significantly restrict supply airflow. Furthermore, the supply riser is not made square to the supply trunk, and in several instances scrap metal cut from the supply trunk was found still partially attached to the trunk further restricting airflow.

The supply register discharge opening in the floor was often partially blocked by interior walls that overlapped the hole or by poorly cut vinyl flooring.

One solution to these problems is to install wider (4-inch) in-line boots. Another option is to convert the in-line boots to short perimeter type flex duct connections.
Investigate using a zip spiral saw for a better method to cut the trunk for the in-line supplies.

3. Tabs: The furnace connection box and rectangular-to-round flex duct take-offs have numerous tabs that are bent over to mechanically fasten these joints. This task is time consuming and involves numerous sharp edges and unnecessary leakage sites. Often the tabs do not get bent over as intended.
   A single bendable flange is superior to many small tabs. Redesign this box without tabs.

   The tabs on the rectangular-to-round flex duct take-offs for the perimeter supplies are too small. Redesign these take-offs with wider or single flaps, which offer a larger target for screw fastening and allow less air leakage.

4. Use a square hole-cutting template that will allow perimeter take-offs to be quickly aligned, directly scored, and accurately cut into the supply trunk.

5. Un-insulated supply duct condensation: Un-insulated supply ducts in the floor system are prone to condensing moisture during air conditioning. Insulating metal supply ductwork reduces condensation, mold and rot potential inside the belly. Any moisture condensing in the floor system can get trapped in place by the bottom board. Specific recommendations follow:
   - Insulate all supply trunk ducts
   - Add a 4-6 inch insulation wrap on the exterior of crossover collars and in-line boots.

6. The perimeter flex duct assembly uses a strap on the inner liner and cloth duct tape on the outer liner. Instead, use mastic foil tape on the inner liner, and a strap and cloth duct tape on the outer liner.

7. The outdoor air ventilation duct is directly connected to the furnace. If this is not changed when the air conditioning A-coil is installed, ventilation air will not receive direct dehumidification, which has been known to result in poor humidity control.

8. Crossover ducts: Recommend using a minimum of R-6 (preferably R-8) crossover duct insulation. Also, use of insulated metal elbows will improve joint durability and significantly improve supply airflow.

9. Tape or cap off duct openings during assembly. This will facilitate testing and keep construction dust from entering the duct openings.

10. Redesign the furnace boot gasket. The gasket between the furnace and the furnace connection boot should be two or three times larger to assure proper sealing.

11. A significant portion of the duct leakage might be redirected back into the home by sealing the perimeter of the bottom board and carefully repairing any penetrations to the bottom board. Currently, air can just as easily leak outdoors as back into the house. If leaking air is directed back into the house, then duct leakage matters less. This may be simpler to accomplish than many other recommendations.

PLANT 10

Summary

Two floors were tested in the plant to measure total duct leakage. The results are shown in Table 1. Total duct leakage was measured at 6.3% and 6.7%. Approximately 45% of this was determined to leak to the outside, resulting in the homes barely meeting the preferred target for duct leakage of 3%. Greater attention to details of sealing connections can ensure meeting this target consistently.

Three additional homes were then set up in the plant lot and tested for duct leakage. Leakage to the outside on these homes was found consistently to fall just below the 3% target rate.

Test Results

Table 1: Results from duct leakage testing

Test home number	Home area (square feet)	Total leakage	Estimated leakage to the outside
1 (in plant)	1,512	6.3%	2.9%
2 (in plant)	1,458	6.7%	3.0%
3 (in field)	1,512	7.5%	2.9%
4 (in field)	1,458	7.8%	2.8%
5 (in field)	1,458	7.4%	2.6%

ADS Efficiency Measures

All air duct connections including the furnace connector, boots (whether prefabricated or produced at the factory), and ends, are sealed with mastic suitable for that purpose. Register boots are sealed with mastic at the duct and at the floor. All seams are sealed with mastic. Flex duct connections are completed as per the manufacturer's instructions and the connections sealed with mastic.

Ends of ducts are capped with a 2x6 block, covered with duct material and sealed with mastic.

Gaskets for through-the-floor crossover ducts are made of foam with a non-porous coating and a minimum diameter of 1-1/2".

PLANT 11

Summary

Three floors were tested in the plant to measure total duct leakage. The results are as shown in Table 1. The average total leakage was less than 50 CFM25, total. These tests indicate excellent duct tightness. With proper crossover connections, these homes will exceed the duct leakage tightness target in the field. While duct leakage to the outside could not be established in the plant, outside leakage on average is about half of the total leakage values. If homes consistently satisfy the duct leakage requirement using *total* leakage values, then it is given that they will also pass the requirements for leakage to the outside.

Test Results

Table 1. Results from duct leakage testing

Test home number	Home area (square feet)	Total leakage	Estimated leakage to the outside
1	1,760	3.8%	~2.0%
2	1,150	3.6%	~2.0%
3	1,170	4.1%	~2.0%

These homes all have total duct leakage levels less than 5% and are anticipated to meet the 3% target level when installed in the field and leakage to the outside can be measured.

ADS Efficiency Measures

Testing total duct leakage in-the-plant through available openings into the ducts: a supply termination on the floor decking (left) and the crossover collar underneath the home (right) can be used to measure low flows with little loss in accuracy. Total duct leakage can be used to estimate leakage to the outside when the home is set up.

Data from field tests show that in each of three field tested homes, less than 40% of total duct leakage leaks to the outside. Several of the ducts in these homes had furnace alignment problems that were repaired with tape. The ducts with mis-aligned furnaces had more leakage than others.

PLANT 12

Summary

This is an extensive facility with two production lines. Generally, the same type of construction is conducted on each line. Some homes are built with ducts in the floor and others with overhead ducts on each line. All of the homes tested in the plant were typically constructed models. The plant had recently invested considerable effort to reduce duct leakage. The success of this initiative is noted in the excellent performance of many duct systems.

Duct systems were inspected and tested from floors in each of the production lines. The resulting duct leakage to the outside was found generally to be between 3% and 5%. It is likely that the plant can bring duct leakage consistently below 3%.

Test Results

Table 1. Results from duct leakage testing

Test home number Line A	Home area (square feet)	Total leakage	Estimated leakage to the outside
1	1,570	4.3%	2.1%
2	1,570	3.5%	1.8%
3	1,570	2.9%	1.5%

Test home number Line B	Home area (square feet)	Total leakage	Estimated leakage to the outside*
1	1,570	8.3%	4.1%
2	1,570	10.1%	5.0%
3	1,570	8.9%	4.5%

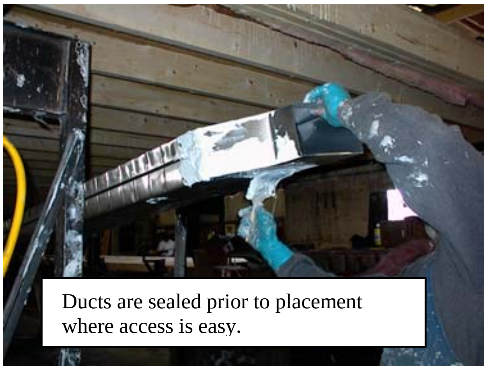
ADS Efficiency Measures

Total duct leakage measured from six floors in the plant averaged 6.3% (total duct leakage/ floor area). A test of three additional homes indicates that less than 40% of this (2.5%) is estimated to leak to the outside.

In two floors with higher leakage rates, the furnace plate had not been positioned directly over the trunk and the resulting gap was bridged with folded metal and tape. This type of repair could account for the excess leakage in these homes.

Homes built without misalignment problems and taped repairs are projected to easily qualify for the 5% duct leakage target. With little additional measures, homes could consistently achieve the 3% duct leakage target.

1. **Maintain excellent duct tightening practices**. The plant is doing many things correctly with regards to duct sealing as part of their manufacturing process. Some examples are illustrated below:



Ducts are sealed prior to placement where access is easy.

Generous amounts of mastic cover all trunk seams.

Mastic is used to cover all take-off boot seams.

Mastic and fiberglass taped seams are allowed to cure before use.

2. **Maintain furnace plate and duct riser seal**. The furnace plate connection is arguably the most important connection to seal. The plant uses a "caulk and screw down" design for both the furnace plate connection and the straight risers. The trunk is not opened until after the connections are secure – resulting in a perfectly aligned hole.

Mastic is applied to the flange of the boot before it is screwed into the trunk.

PLANT 13

Summary

The plant has demonstrated the capability to produce homes that have duct leakage to the outside below 5% (two tested around 1%, and the third at 4.9%). Minor modifications in the installation process should enable the plant to achieve the 3% target consistently (the third unit had slight punctures in the crossover). These modifications will be included in subsequent plant quality control documents.

Testing Results

Field and plant testing and inspections were conducted on December 18 and 19 to verify that the plant is capable of consistently producing homes to these standards.

Table 1. Results from duct leakage testing

Test home number	Home area (square feet)	Estimated leakage to the outside
1	1,568	0.6%
2	1,680	1.3%
3	1,456	4.9%

* Duct leakage for test home #3 (tested in the field) was traced to staple punctures in the crossover duct. This was brought to the attention of the installer.

ADS Efficiency Measures

- Provided instruction on how to use the duct blaster during three field tests
- Illustrated common problem areas affecting duct tightness
- Provided guidance to minimize measurement error when pressure testing
- Reviewed plant manufacturing and installation process
  i. Ductwork is mastic sealed, transition crossover is flex duct
  ii. Flex used on duct crossover (installed by plant in manufacturing process)

PLANT 14

Summary

Two floors in the plant and two homes set up in the field were tested for duct leakage. The results from measured leakage (from the two homes set up in the field) showed an average of 2.5% leakage to the outside. These homes meet the preferred targets for duct leakage of 3%. However, the two homes tested in the plant showed a higher total duct leakage and have an estimated leakage to the outside of 4.4%. All of these homes achieved the target 5% duct leakage. Methods to improve duct sealing were demonstrated that could consistently result in less than 3% leakage for all the homes.

Test Results

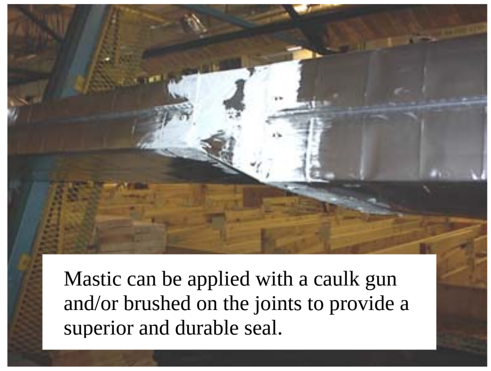
Table 1. Results from duct leakage testing

Test home number	Home area (square feet)	Estimated leakage to the outside
1 (in plant)	784	4.2%
2 (in plant)	896	4.5%
3 (in field)	1,740	2.3%
4 (in field)	2,128	2.6%

Note: In-plant test assumes 50% of total leakage is to the outside. Single floor test includes the air handler connections. Data from the two field tests shows the outside leakage fraction to be 37% of the total leakage. If this were consistent for the homes tested in the plant then the estimated duct leakage to the outside would be 3.1% and 3.3% for these homes.

ADS Efficiency Measures

1. **Trunk assembly**
The plant pre-builds most of their duct systems and stores them on a rack prior to insertion into the floor system. A smoke test at this point revealed that several of the connections leaked – particularly the duct graduation connectors and the branch sections – even though the plant is already using a curable sealant on the connections. This is an ideal application for brushed-on mastic to provide superior sealing of the metal duct system. A more thorough application, using a brush, for critical connectors using the current sealant material should result in similar improvement.



Mastic can be applied with a caulk gun and/or brushed on the joints to provide a superior and durable seal.

2. **Perimeter Supply Assembly**
The perimeter supplies are made using rigid metal collars, flex duct and metal boots. No leakage was observed in this part of the duct system.

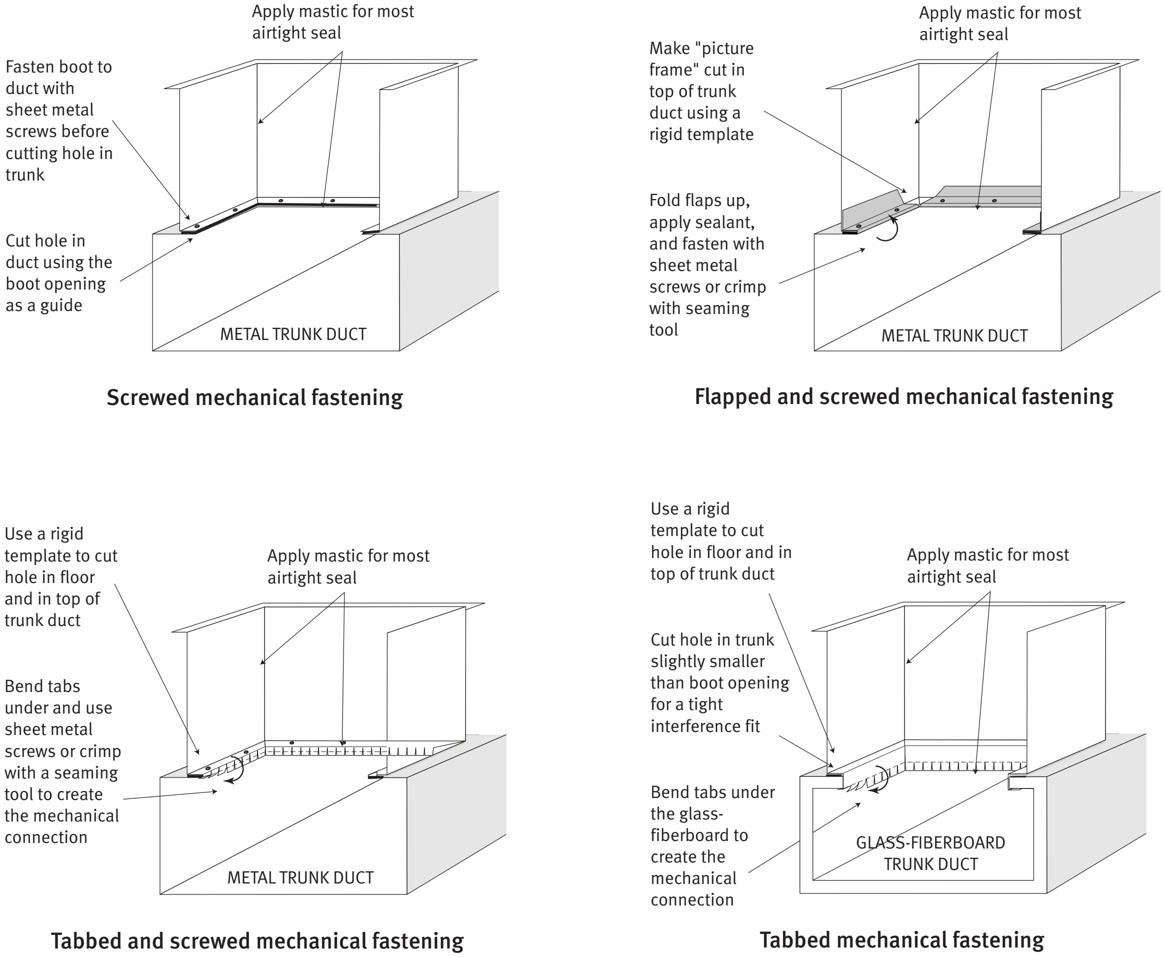
3. **Crossover System**
The plant is using a 12” diameter flexible crossover attached to a metal collar from each section’s main trunk. The set up checklist should stipulate specific requirements to make this a durable, airtight seal.

4. **Furnace Connection**
The furnace base is potentially the worst leak site in the duct system. The plant is currently making a successful furnace seal by paying close attention to detail.

   The following are alternative recommendations for leak free furnace plate assembly: MHRA recommends making a “picture frame cut” into the trunk and screwing it into the side of the furnace base, and sealing with mastic. This is a superior performing and more durable connection. (See Figure 5.4 from MHRA publication ***Duct Systems: Guide to Best Practices*** for a good illustration.)

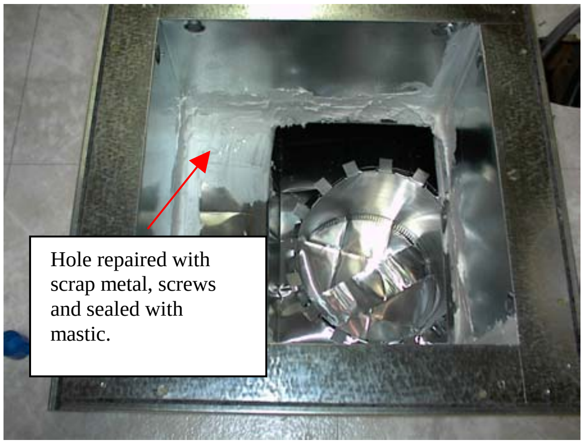
Fold trunk into furnace plate and fasten together with screws. Seams are then visible and more easily sealed.

Figure 5.4 Furnace Boot Connections



The furnace manufacturer should review this recommendation.

In cases where the furnace plate misses the trunk, care needs to be taken to avoid creating hard to seal holes (as shown below). The chance of creating such difficult to seal holes can be minimized by using wider trunk ducts.



Branch ducts have zero clearance for saw cut through floor sheathing; the picture frame cut cannot be used.

Cardboard spacer provides clearance for later saw cut through floor sheathing.

When the furnace is located over a branch duct, cutting through the floor sheathing can result in cutting through the duct, thus preventing the picture-frame-cut fastening method. A cardboard spacer installed earlier in the process will prevent accidental cut-through.

PLANT 15

Summary

The plant uses a fiberglass duct board trunk system with side-mounted branch takeoffs and R-4.2 flex duct branch connectors attached to standard floor boots. Total duct leakage was measured at 274 CFM25, corresponding to a 32% cfm/ft^2 duct leakage (16% to the outside). This duct system did not meet the target of 3% to 5% leakage. The following list of measures was reviewed during the plant visit and was recommended to achieve performance at the required leakage levels. Duct leakage levels of 5% or less were obtained on homes tested subsequent to the implementation of ADS improvements as seen in Table 1 below.

Test Results

Table 1. Results from duct leakage testing

Test home number	Home area (square feet)	Estimated leakage to the outside
1	1,680	4.5%
2	1,904	4.9%
3	1,120	4.7%

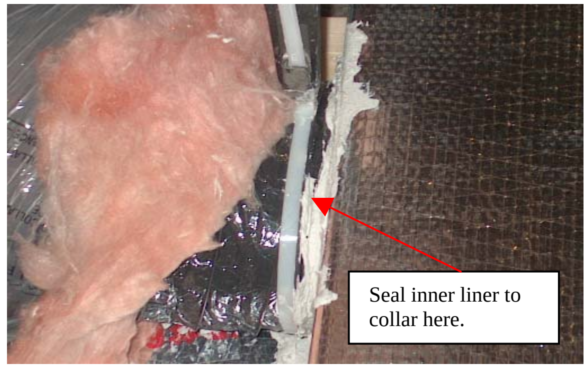
ADS Efficiency Measures

1. **Seal side mounted collars.** Fiberboard systems rely on tabs folded into the duct for mechanical fastening. These tabs are less rigid than screw-type fastenings and increase the difficulty in sealing. Tapes designed for metal to fiberboard attachment may be used for sealing the collars and some manufacturers have had good success with this method. The other method (practiced at this plant) is to apply enough tape to secure the collar at the top and bottom and to apply a liberal layer of mastic completely covering the tape.
   The tape will support the duct during construction in the plant and the mastic will eventually cure to form a durable strong seal. However, mastic curing could take several days depending on temperature and humidity conditions.

It is difficult to create a durable seal using tape or mastic alone.

Applying tape as a temporary seal then covering the seam and tape with mastic will result in a superior and durable seal.

2. **Secure and seal the flex duct to the side-mount collars.** The inner liner of the flex duct should be fastened and sealed. Tape may work in this location if a plastic strap is used over it; otherwise mastic makes a good seal here. The inner liner should first be placed on the collar and attached with a plastic strap to hold the liner in place.



3. **Use care and attention to detail in crossover branch connections**. This is a critical area for leak prevention. Apply a good quantity of mastic between the mating surfaces of each trunk. Accurately cut the holes and use metallic channel to serve as a mechanical attachment. The channel should be sealed with mastic along all exposed edges. Strap the two trunks securely to prevent any movement of the duct until the mastic has had sufficient time to cure. Installers should be made aware that the mating surfaces are relatively fragile and may open if any pressure is applied to either trunk prior to curing.

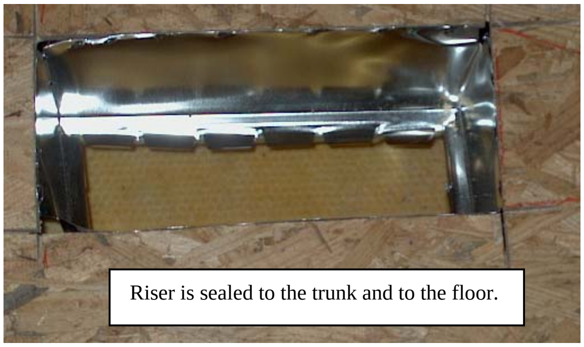

Metal channel is fit in place prior to covering with mastic.


Trunk-to-trunk connections are subject to damage during construction. Take care not to disturb.

4. **Seal in-line boots to the trunk and to the floor.** Apply mastic to in-line risers prior to installation with a caulk gun. Steps are as follows: cut a properly sized hole into the trunk, apply mastic, install riser, and fold up tabs to complete the sealing. Other risers are available that are easier to seal and less prone to being messy.

   All openings between the boot and the floor should be sealed. These small holes can add up to significant duct leakage.


Apply mastic to riser prior to installation. This riser style has a "hip" for mastic and is less messy than finger tabs.



Riser is sealed to the trunk and to the floor.

Many small holes can add up to significant duct leakage.

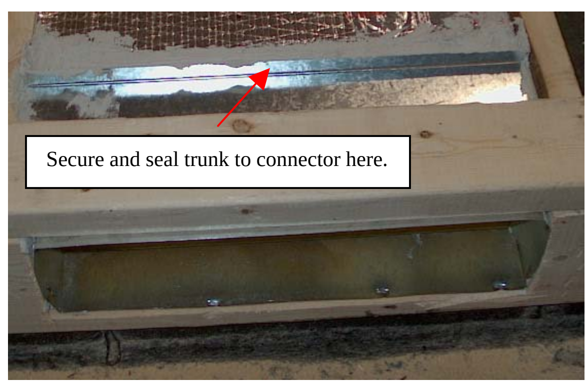
5. **Redesign the furnace plate/plenum to the duct board connection**. The furnace connection is often the leakiest site in the duct system. One option is to manufacture a metal channel designed to attach the inside of the duct board material and the plenum sidewall. The channel should be secured with screws and sealed with mastic.

   Other manufacturers are having success using liberal amounts of mastic applied by gloved hand to the folded finger tabs of the existing furnace plate.

Furnace plate prior to sealing to trunk with mastic.

Furnace plate after sealing to trunk with mastic.

6. **Use care and attention to detail in crossover connections termination in the rim joist.** Care must be taken to insure that the duct board material is not pushed away from the metal connector or duct leakage will be excessive. A heavy application of mastic is recommended on both sides of all mating surfaces to assure proper sealing. Tape may be used to hold the material together while the mastic is curing. Cover all tape edges with mastic.



Secure and seal trunk to connector here.

PLANT 16

Summary

Some homes built in this large facility have ducts in the floor and others have overhead ducts. All of the homes tested in the plant were typically constructed models. The plant had recently invested considerable effort to reduce duct leakage on all of its production plant-wide. The success of this initiative is noted in the high performance of typical duct systems.

During the plant visit the duct leakage to the outside was found generally to be between 3% and 6%. It is likely that the plant can bring duct leakage consistently below 3%.

The plant experimented with many ways to seal ducts consistent with their production process.

Test Results

Table 1. Results from duct leakage testing

Test home number Line A	Home area (square feet)	Total leakage	Estimated leakage to the outside
1	2,010	6.3%	3.1%
2	2,010	6.5%	3.2%
3	2,010	11.4%	5.7%

Test home number Line B	Home area (square feet)	Total leakage	Estimated leakage to the outside
1	2,379	7.6%	3.8%
2	2,379	5.3%	2.7%
3	752	7.45%	3.7%

Several ducts had furnace alignment problems that were repaired with tape. These ducts had more leakage than others.

ADS Efficiency Measures

Total duct leakage measured from six floors in the plant averaged 7.4% (total duct leakage/ floor area). A test of three additional homes located in the field indicated that less than 40% of the total duct leakage is estimated to leak to the outside.

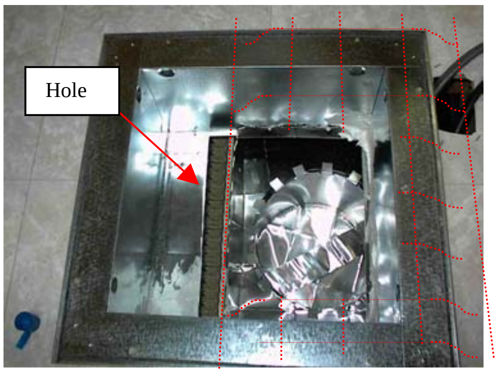
One floor had higher than average duct leakage of 5.7%. In this floor, the furnace plate had not been positioned directly over the trunk and the resulting gap was bridged with folded metal and tape. This type of repair could account for the excess leakage in this home.

Homes built without misalignment problems and taped repairs are projected to easily qualify for the 5% duct leakage target. With a few additional measures, homes could consistently achieve the 3% duct leakage target.

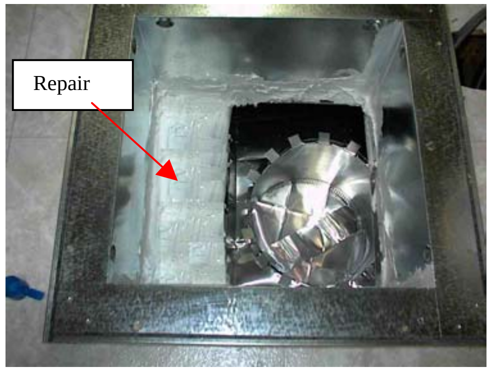
1. **Avoid trunk misalignment and use better repair methods for the occasional misalignment.** Trunks were found that had been misaligned in the floor section and required

repair when the furnace plate was installed. If training does not resolve the alignment problem, consider a template or a guide that makes proper trunk alignment easier to obtain.

Repairs currently being made with tape should be made using scrap metal and mastic as shown below.



Hole left due to misalignment of trunk with furnace base.



Hole repaired with scrap metal, screws and mastic.

2. **Don't overuse fiberglass tape.** Fiberglass tape is used to strengthen a connection. There is no need to strengthen the end cap connections. The tape can hide a poorly sealed seam. End cap seams will be better sealed by mastic alone.