Truss-Integrated Thermoformed Ductwork - AWARD NO. DE-FG02-01ER83325

A multi-year research project was undertaken to develop a leak-free duct system that can be readily installed within the thermal envelope. This project sought to make a significant stride beyond other initiatives focused on improving the tightness of conventional duct systems with various sealing techniques. The primary objective of this research project was to develop a leak-free, low-friction plastic residential duct system that is cost-effective and easy to install within the home's thermal envelope. This project introduced the use of smooth internal surface, low friction plastic ducts that could be easily installed in above-grade residential applications with very low air leakage.

The initial system concept that was proposed and researched in Phase I focused on the use of thermoformed plastic ducts installed in a recessed roof truss underneath the attic insulation. A bench top thermoformed system was developed and tested during Phase I of the project.

In Phase II, a first generation duct system utilizing a resin impregnated fiberglass duct product was designed and specified. The system was installed and tested in an Atlanta area home. Following this installation research and correspondence with code officials was undertaken to alleviate the continued concern over the code acceptance of plastic ducts in above ground applications. A Committee Interpretation response was received from the International Code Council (ICC) stating that plastic ducts were allowed, but must be manufactured from materials complying with Class 0 or Class 1 rating.

With assurance of code acceptance, a plastic duct system using rotomolded high density polyethylene ducts that had passed the material test requirements by impregnating the material with a fire retardant during the molding process was installed in the basement of a new ranch-style home in Madison, WI. A series of measurements to evaluate the performance benefits relative to a similar control house with a standard sheet metal installation were made.

This research concept is not ready to a preproduction stage. The air leakage and fan energy performance benefits of plastic ducts are apparent. However, the round ducts do not readily integrate with current residential construction details. A code-approved plastic material is available, but the addition of flame retardant adds significant cost. The ultimate cost of the system has yet to be defined well enough to assess the marketability of plastic duct systems.

Long-term plans for commercialization should include action to initiate code language modifications that specifically address above-grade installation of plastic ducts. The American Plastics Council has demonstrated interest in this project and could potentially support a code modification effort. The justification for the Class 0 or 1 material classification requirement should also be researched further to determine if there is any opportunity to eliminate the requirement which adds significant cost to the product.

Truss-Integrated Thermoformed Ductwork

PHASE II Final Technical Report

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August 30, 2007

Prepared for

THE U.S. DEPARTMENT OF ENERGY
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NOTICE

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Executive Summary

This report summarizes a multi-year research effort to develop a leak-free duct system that can be readily installed within the thermal envelope. There are numerous efforts underway to improve duct system efficiency. Most of these involve modifications to current technology such as air sealing techniques like mastic and aeroseal, snap together duct connections, and greater levels of insulation. This project sought to make a more significant stride forward by introducing a duct system of a material that can be more readily sealed and can exhibit lower friction losses. The research focused on the use of smooth internal surface, low friction plastic ducts that could be easily installed with very low air leakage.

The initial system concept that was proposed and researched in Phase I focused on the use of thermoformed plastic ducts installed in a recessed roof truss underneath the attic insulation. A bench top thermoformed system was developed and tested during Phase I of the project.

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Statement of Problem

Residential duct systems are notoriously inefficient. Studies have shown that typical duct systems lose over 30% of the space conditioning energy through air leakage and conductive heat transfer.[1] In California, where utility programs and incentives have produced reductions in duct leakage, leakage values are still 20% to 25% of total system air flow in 70% of the new homes.[2] All across the South and Southwest, where cooling loads dominate and most homes have slab foundations, HVAC ducts are located above the ceiling insulation in the hot attic. This practice has moved to the North as well with the greater presence of central air conditioning. For attic installations, flex(ible) ducts are typically used and are often only insulated to R-4.2. Codes are beginning to require greater levels of insulation, but the ducts become very bulky and, as demonstrated in testing by ORNL, are degraded by tight bends, “squeezed” ductwork and damaged

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[1] Jump, D.A., I.S. Walker, M.P. Modera. “Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems.” Proceedings of the 1996 ACEEE Summer Study, Vol. 1, pp. 147-155.

[2] Hedrick, R. “Home Builders Guide to Ducts in Conditioned Space.” California Energy Commission, 500-03-082-A16, October 2003.

insulation.[3] The flexible ducts also have high friction coefficients dictating large sized ducts to limit air handling equipment external static pressures.

The Heating, Cooling, and Commercial Refrigeration program element within the Building Technologies Program "seeks to accelerate the development and introduction of highly efficient heating, ventilating, refrigeration, and air-conditioning systems, and water-heating technologies." In the industry roadmap[4] which guides DOE's R&D activities, a 50% reduction in duct losses is a critical element for achieving the goal of a 50% reduction in HVAC annual energy consumption and peak electric energy demand in new residential buildings by 2020. This research project to develop a leak-free duct system that can be readily installed within the thermal envelope directly addresses that important industry goal and EERE's mission to strengthen America's energy security, environmental quality, and economic vitality.

Project Objectives

The primary objective of this research project is to develop a leak-free, low-friction plastic residential duct system that is cost-effective and easy to install within the home's thermal envelope. Plastic ducts can offer significant benefits over today's conventional sheet metal, flex duct, and ductboard systems:

- Plastic ducts are potentially leak-free. Easy and effective methods for sealing plastic pipe are known. The problems with excessive air leakage in today's duct systems have been well documented.
- Plastic ducts with smooth interior surfaces and curved take-offs and turns will have lower friction losses than typical flex duct, duct board or sheet metal systems. This may be translated into smaller duct sizes (less material cost) and/or reduced fan energy requirements (operating cost savings).
- Systems can be prefabricated to reduce the effort and skill levels required in the field and reduce cycle time.
- Plastic ducts are durable and can be easily cleaned to alleviate health concerns over dirt accumulation and potential mold growth.

In the context of a stage-gate development process, the new plastic residential air distribution system has the following "must meet" criteria to proceed to the next product development stage:

- eliminate the air leakage inefficiencies of today's sheet metal and flex duct systems,
- readily integrate with current residential construction practices,
- be acceptable to code-enforcement officials, and
- meet industry standards for marketability.

Technical Approach

The key elements of SWA's technical approach to this research were to answer the following questions:

- o Can a material be found that meets the specification criteria of strength, formability, fire resistance, and cost?

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[3] *"Whole-Duct-System" R-Values*, Energy Design Update, December 2004, pp.4-5.
[4] "HVAC&R Research for the 21st Century," Air-Conditioning and Refrigeration Technology Institute, Inc., November 2004, http://www.arti-21cr.org/documents/roadmap.pdf.

- o Are there building code issues that represent significant hurdles?
- o Are the benefits significant enough to warrant market transformation?
- o Will builders and trades readily value and accept the concept?

There are numerous efforts underway to improve duct system efficiency. Most of these involve modifications to current technology such as air sealing techniques like mastic and aeroseal, snap together duct connections, and greater levels of insulation. This project sought to make a more significant stride forward by introducing a duct system of a material that can be more readily sealed and can exhibit lower friction losses. SWA has been contacted by interested duct system manufacturers, builders, and the plastics industry - suggesting that this research is unique and important.

The initial system concept that was proposed and researched in Phase I focused on the use of thermoformed plastic ducts installed in a recessed roof truss underneath the attic insulation. This design of a one-piece array that would fit into recessed truss limited its applicability to certain house designs and required changes to today's construction sequence practices. It also involved significant amounts of sheet material that did not carry or transfer air which added unnecessary cost and weight to the system. It was determined early in the Phase I research that a preferred approach to thermoforming the ductwork is to form a limited number of standardized duct system components that can be connected into configurations more similar to conventional duct layouts.

Thermoforming was used to produce two different duct shapes. These were bonded together to form a duct system and testing demonstrated that the system was essentially leak free. A complete Phase I report documenting the findings on materials research, thermoforming technology research, and detailing the system fabrication process and testing was submitted in mid-2002 and is provided as an Appendix to this report.

The following are the specific technical objectives for the Phase II research:
- o Determine optimum set of standardized duct components for system flexibility with a minimum number component types and thus molds.
- o Select the final candidate plastic material(s).
- o Study building codes and standards; develop strategies for code approvals.
- o Install and evaluate a prototype whole house duct system.

The following is a timeline of significant accomplishments during the Phase II research and each of these will be discussed in the following sections.

- In 2003, SWA designed and specified a first generation duct system utilizing a resin impregnated fiberglass duct product. The system was installed in an Atlanta area home and tested in January 2004.
- Early in 2004, SWA was approached by a small plastic product manufacturer, Pinnacle Plastic Products, with interest in entering the HVAC market.
- Throughout 2004, SWA researched and corresponded with code officials to alleviate the continued concern over the code acceptance of plastic ducts in above ground applications.
- In July 2005, a Committee Interpretation response was received from the International Code Council (ICC) stating that plastic ducts were allowed, but must be manufactured from materials complying with Class 0 or Class 1 rating.
- In January 2006, SWA became aware of CDC Enterprises and their rotomolded high density polyethylene ducts that had passed the material test requirements

by impregnating the material with a fire retardant during the molding process.

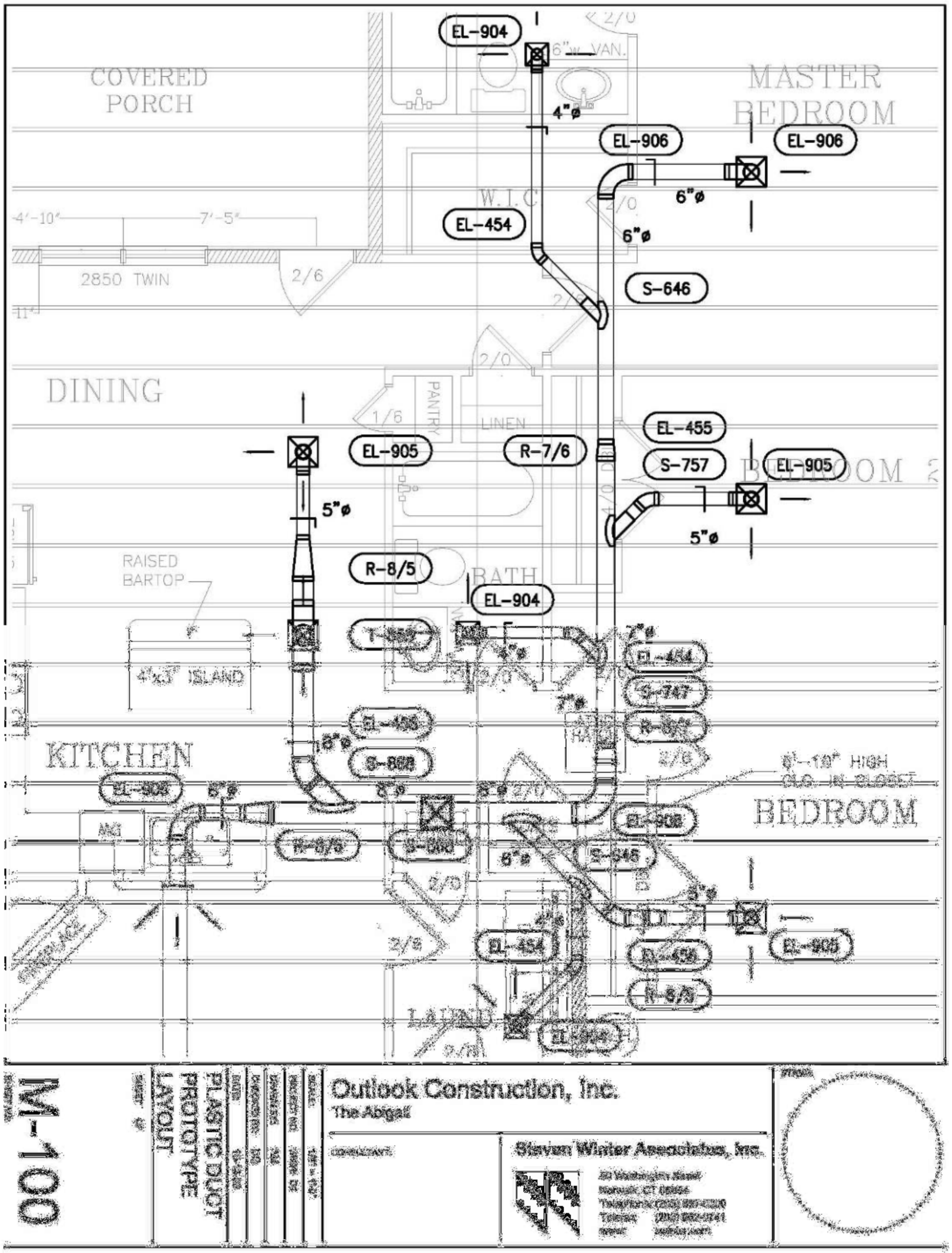
- During the summer of 2006, a plastic duct system using CDC Enterprises' product was installed in the basement of a new ranch-style home in Madison, WI. SWA made a number of measurements to evaluate the performance benefits relative to a similar control house with a standard sheet metal installation.

First Generation Duct System (Outlook Construction Installation)

SWA successfully integrated a plastic duct system into a new Outlook Construction home in Cartersville, GA. At the time, Outlook Construction was actively working with SWA as a builder partner with the CARB Building America team. SWA designed the system which used components commercially available from ATS Products, Inc. of California (www.atsduct.com). The ATS-FRP™ duct is composed of fiberglass saturated with chemical and fire resistant resins. This product is typically used for highly corrosive exhaust applications and thus over-designed and too expensive for residential application. However, the product had the necessary UL 181 rating and provided the opportunity to evaluate installation issues and market receptiveness.

Outlook Construction home.

ACCA Manual J and D procedures were used to design the system. Higher velocity and pressure limits than would normally be used were applied To aid in the testing and balancing of this unique system, Fantech Iris dampers were installed.



ACCA Manual J and D based HVAC Design

The system, shown in the following photographs, was met with enthusiasm by Meadows Heating and Air Conditioning, the mechanical contractor utilized by Outlook Construction for standard installations, as well as the local inspectors who visited the site during the installation.

ATS Duct Components

Cutting opening for saddle-type take-off.


Saddle-type take off riveted to trunk.


Red slip collar for connecting ducts.

Joints covered with fiberglass tape and mastic.

7" to 6" reduction with adjustable iris damper.

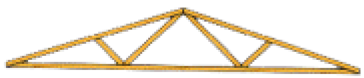
Branch take-off to register boot.

Duct support and turn to conventional register boot.

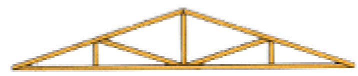
The 90° turn to the register boot required that the supply trunk be raised. Supports were made onsite for this purpose. The height of these supports varied as the trunk transitioned to smaller diameters. This was a rather tedious step in the installation process.

Conventional duct systems installed in attics use lightweight flexible ducts hung by straps from the trusses. While this approach is not energy efficient with long duct runs having many turns and kinks, it is easier to install. There are also side entry register boots that could have reduced the needed height of the trunk lines.

For an attic installation of a rigid duct system, it is important that the home uses roof trusses that provide an open area in the center of the attic. A "W" or Fink truss, which is commonly used in residential construction, accomplishes this. However, a Howe truss does not.



"W" or Fink Truss



Howe Truss

The plastic ducts were ultimately insulated with a polyurethane spray foam. This insulation method was first performed as a CARB advanced systems research initiative earlier in the year.

Application of polyurethane foam prior to blowing attic insulation in another Outlook home.

Upon completion of the duct installation and prior to insulation, SWA engineers performed testing primarily to quantify air leakage and confirm that the system was properly balanced. Measurement equipment included the Tru-Flow grid, LoFlo balometer, and duct blaster. The following is a summary of the measurements:

- The Tru-Flow grid indicated a total air flow of 500 to 550 cfm.
- The duct blaster indicated approximately 100 cfm total duct leakage at 25 Pascals
- The sum of the LoFlo balometer measurements at each supply register was 400 cfm.

The fact that the measured duct leakage is equal to the difference between the Tru-Flow and the balometer measurements is believed to be a coincidence. It is suspected that the balometer readings may have been low. The pressure drop across the iris dampers suggested higher values although they were not installed with adequate straight duct lengths for calibration purposes. It has been reported by Lawrence Berkeley National Laboratory[5] that measurements with this balometer are not reliable especially for swirling air flows. All of the supply registers in this home were three-way ceiling registers which would produce a swirling pattern in the flow hood.

Never the less, the duct leakage was excessive and actions were taken to reduce it including:

- Inspecting the ducts in the attic for obvious leakage locations
- Sealing the air handler cabinet with tape
- Foam sealing the register boots to the ceiling sheet rock
- Wrapping the iris dampers with gasket material that could be removed for adjustment and reapplied

However, these actions did not result in a significant improvement. The conclusion to date is that numerous small leaks existed throughout the system.

Assuming that the distribution of air to the supply registers based upon the balometer measurements was in good agreement with the initial design. No adjustment of the iris dampers was necessary. ACCA Manual D calculations with higher velocity and pressure limits than would normally be applied are adequate for duct design.

To qualitatively test the potential for noise with smaller ducts and higher air velocities, nearly half the supply registers were blocked to double the air flow to the remaining registers. Only the bathroom supply with an air velocity of 630 feet per minute exhibited significant noise.

The high material cost of the duct system and the relatively tedious installation of branch take-offs made this installation far from being commercially viable. However, this installation did provide insights into important design and building integration issues.

Manufacturer Interest (Pinnacle Plastic Products)

Early in 2004, Steven Winter Associates, Inc. (SWA) was approached by Pinnacle Plastic Products (PPP), a small manufacturing firm in Ohio, with interest in further

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[5] *Evaluation of flow hood measurements for residential register flows,* LBNL-47382.

developing the plastic duct concept. This firm, which primarily supplies blow-molded plastic components to the car industry, was interested in expanding to a new market.

Blow-molded automotive components by Pinnacle Plastic Products

PPP initially became interested in the idea of plastic ducts for residential applications when they were developing plastic components for automobile heating, ventilation, and air conditioning (HVAC) applications. As a small company, PPP was looking for an opportunity to diversify their product line and make themselves less reliant on shifts in the automotive industry. A search for information on plastic ducts led PPP to SWA and the two firms began to develop the concept further.

The product development discussions focused on:

- Appropriate Material Selection
    - Temperature
    - Deflection
    - Weight per linear foot
    - Cost
    - Flame & Smoke Spread
- Potential for incorporating recycled materials
- Reduction in required duct sizes due to reduced pressure drop
- Connection and Fitting Design
- Options for Insulating the Ductwork

PPP feels there is a strong market for this type of product and wanted to partner with SWA to manufacture and install a prototype duct system. However, there were two major roadblocks delaying the manufacture of prototype components – cost and code.

To address the cost concern, SWA provided PPP with a schematic design of a very basic system. The system design was based on a floor plan provided by a large homebuilder interested in installing a prototype HVAC system in a single story, ranch-style home. To reduce costs, SWA limited the number of fittings and sizes to the minimum amount required. Based upon this design, PPP determined the costs for the number of molds that would need to be designed for a single prototype. As a small firm, PPP did not have the necessary funds to cost share the investment in new molds.

PPP spoke with a number of Tool and Die Makers to gauge interest in the project and find partners willing to discount the mold costs. PPP also contacted a local technical school to discuss the possibility of having students design the molds at a reduced cost. These efforts were not successful, but demonstrate PPP's relatively high level of interest.

The second roadblock was code restrictions and SWA's research to address this barrier is described in the following section.

Code Compliance

At the outset of this project, building industry professionals were skeptical that a plastic duct system would pass building codes. SWA researched the requirements of both the 2003 International Residential Code (IRC) and the 2003 International Mechanical Code (IMC) regarding air duct systems.

While the IMC does not govern residential duct systems, it explicitly states that "Plastic duct and fittings shall be utilized in underground installations only." The IRC does not prohibit plastic ducts above-grade, but only discusses plastic ducts as underground ducts. In certain regions of the country, plastic ducts are commonly used under slab foundation homes.

Plastic (PVC) ducts in the Chicago area prior to pouring of slab foundation.

This ambiguous code language is a potential barrier that is of concern to potential manufacturers and impacts their willingness to commit to the development of product. SWA felt it prudent and necessary to research the rationale for the code language justification and further define material specifications.

SWA contacted the International Code Council (ICC) and it was suggested that SWA pursue a "Committee Interpretation" on the issue of plastic ducts. Committee Interpretations represent the official position of the ICC but in all cases, the final authority on matters of interpretation is the code official. SWA elected to pursue the Committee Interpretation so that there would be supporting documentation for the local code inspector at the time of the prototype plastic duct installation. SWA submitted a letter to the Interpretations Committee on July 20, 2004. A year later, on July 18, 2005, SWA received a Committee Interpretation which states that plastic ducts are allowed above grade but must be made from materials complying with Class 0 or Class 1 rating.

Class 0 materials have surface burning characteristics of 0 (flame spread and smoke developed). Class 1 materials shall have a flame spread index of not over 25 without evidence of continued progressive combustion and a smoke-developed index of not over 50.[6]

The UL181 standard also includes a flame penetration requirement for Class 0 or Class 1 material ducts. The passage of flame is not permitted for a period of at least 30 minutes when tested according to the procedures outlined in the standard.

Commonly used plastics such as polyvinylchloride (PVC) and high-density polyethylene (HDPE) can not meet these requirements. PVC has a low melting point. HDPE is very inert, a self-extinguishing material, and can withstand temperatures in the range of 185°F to 190°F, but this is not adequate. Material additives are necessary for code compliance. These add cost and significant complexity to the manufacturing process.

CDC Enterprises, Inc.

With additional research, SWA became aware of the need for high quality duct for the high velocity system market led by Unico and SpacePak. The higher operating pressures of these systems demand a tighter duct system. Mestek, SpacePak's parent company, had been using a round rigid fiberglass duct supplied by Johns-Manville until the manufacturing plant burned. In Fall 2004, Mestek introduced the GR8 Red Plenum Duct as its new plenum duct. This HDPE duct wrapped with a fiberglass blanket was falsely advertised by Mestek as UL181 code compliant and the product was soon removed from the market. At that time, the product had only passed the UL 723 burn test to the outside of the product.

The primary developer of the GR8 duct, CDC Enterprises, continued to experiment to develop a product that would meet the UL181 requirements. CDC Enterprises is based in Zimmerman, Minnesota and their primary product is AKDUCT™. These HDPE ducts are rotationally molded and extruded for under-slab applications (see photograph). Through research and experimentation, CDC developed HDPE-based ducts that pass the material test requirements by impregnating the material with a fire retardant during the molding process. CDC plans to introduce this product to the market as QADUCT™. A preliminary product brochure is provided as an Appendix.

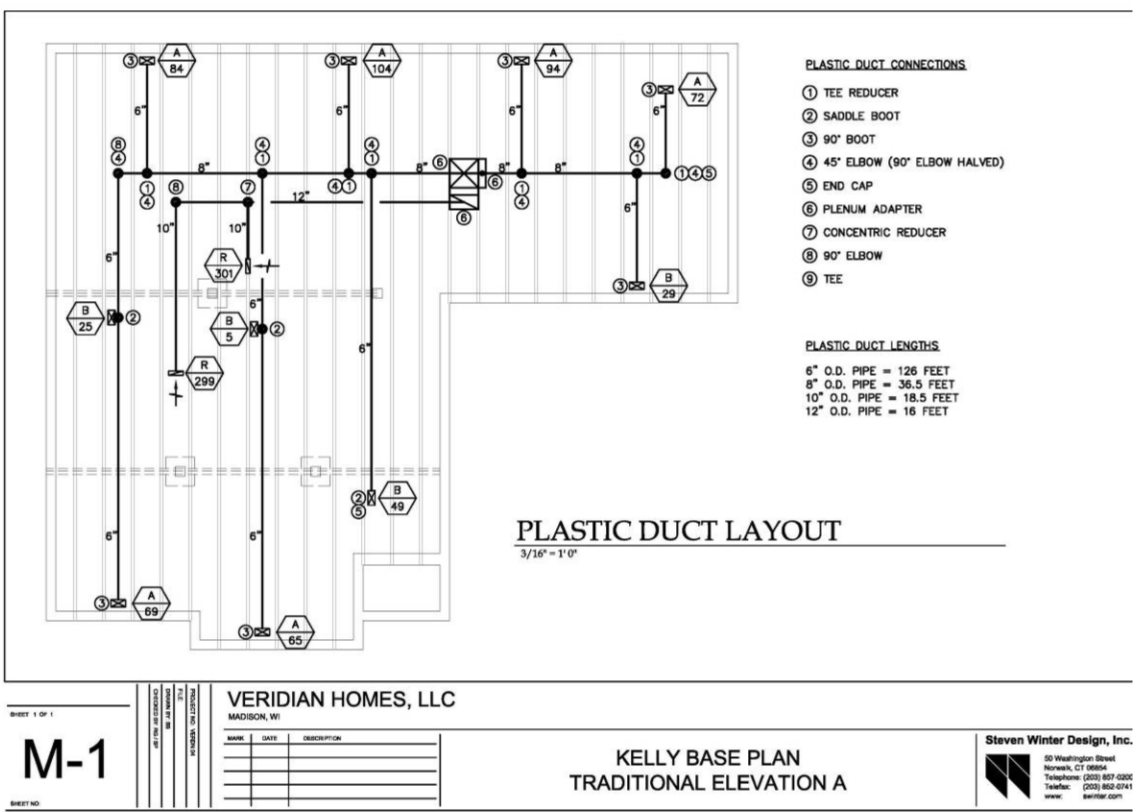
6 Factory-Made Air Ducts and Air Connectors - UL 181.

AKDUCT™ **installation in California.**

Second Generation Duct System (Veridian Homes Installation)

Veridian Homes of Madison, Wisconsin, another Building America CARB team builder, has long been interested in the plastic ducts concept and provided a ranch-style home with a full basement as a test bed for the CDC QADUCT™ system. SWA provided a duct design for the home and, in early June 2006, SWA oversaw and assisted with the duct system installation. CDC provided all of the duct components at no cost. A conventional sheet metal system was installed in another house of the same plan nearby providing comparison opportunities.

Veridian Ranch-Style Home



ACCA Manual J and D based Duct Design for Veridian Home

CDC Enterprises' rotomolded and extruded QADUCT™ Components

Components connected by a self-adhesive gasket and clamp system

Supply Trunk and Return Plenum

Supply Branch Take-offs

Spacing not always ideal for running between floor joists.

Sheet metal system with panned return in control house.

Smoke test indicating leakage at the take-off joint.

As shown in the photographs, the central duct hugs the underside of the floor joists and the supply branches were run up between the joists. The installation time for the plastic duct system was approximately half that of the sheet metal system (3 hours instead of 5 to 6 hours). The ducts can be cut with a utility knife.

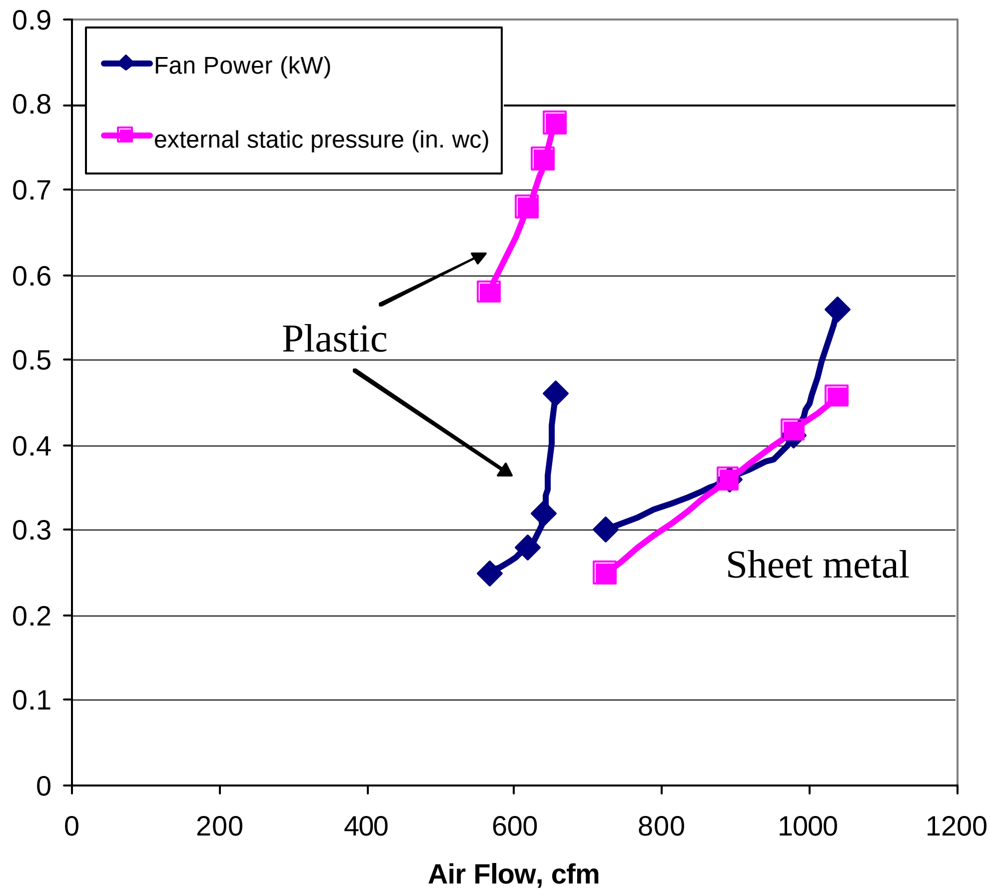
In some instances where branches were in adjacent bays between floor joists, several transition pieces and clamps were needed. There is obviously opportunity for further reducing the installation time. With a mature product market, more duct sizes and fitting configurations will become available.

SWA performed a series of tests to quantify the performance of the plastic duct system in contrast to a traditional sheet metal system installed in another Veridian home of the same plan.

An Alnor LoFlo balometer was used to measure the air flow at each register in both the plastic duct and sheet metal (control) homes. The following table compares the results for the two homes to the initial ACCA Manual J design values. Even though product availability restricted the design to two different supply branch diameters, either 4.5-inch or 6.5-inch internal diameter, the system matched the design values quite well – much better than the sheet metal system.

	Riley Supply Flowrates		
rooms	Plastic Ducts (measured cfm)	Plastic Ducts (design cfm)	Control (measured cfm)
Foyer	47	59	54
Bedroom 2	72	80	84
Bedroom 3	50	57	60
Common Bath	14	3	45
Living Room	72	97	94
Dining Room	74	85	100
Kitchen	60	53	37
Laundry	10	11	39
Master Suite	76	78	124
Master WIC	15	8	-
Master Bath	30	27	60
Basement 1	-	-	25
Basement 2	-	-	26
	520	558	748

A duct blaster test was done to quantify total duct leakage. The plastic duct system had an impressive low total leakage of only 38 cfm while the sheet metal system was 574 cfm. In both homes, the leakage to outside is negligible because the systems are in the basement and the envelope is very tight. Thus, the high leakage to the conditioned space may not be considered a direct energy loss, but it impacts balancing between rooms and fan energy use as shown in the following graph.



As was expected, the external static pressure was significantly higher for the plastic duct system because of the smaller diameter ducts used. What was not expected, is the somewhat lower fan power measurements for the plastic duct system. The air handler for the plastic system was set on its lowest setting, drawing 0.25 kW. In the sheet metal home, the air handler was set on the medium low setting to account for all of the air leakage and was drawing 0.35 kW. This is counter intuitive, but a possible explanation is that the higher static pressure moves the fan performance to a more efficient point on the fan curve. It is not known whether systems are typically operating at non-optimum fan efficiency levels or whether this was a unique circumstance.

Initially, a 64,000 BTUH output furnace was installed in each home. This furnace is oversized for the home's design heating load. Another consideration when determining the capacity of the furnace is the supply air temperatures. At the 750 cfm supply air flow of the control house, the furnace can provide a 79°F temperature rise or approximately 150°F supply air. This is on the high side. At the 520 cfm supply air flow of the plastic ducts home, the temperature rise is excessive. A smaller, 42,800 BTUH output, furnace needed to be installed. This could eventually represent a reduction in system installed cost.

Ultimately, the initial QADUCT™ system needed to be removed and replaced because of problems with leaching of the fire retardant material. Improvements in the extrusion process were made and the system was replaced with a combination of extruded plastic pipe that includes the fire retardant and traditional AKDUCT™ fittings. The AKDUCT™ is CDC's primary product for below grade slab installation. The code language is such that the duct needs to pass UL181 standards, but the fittings do not.

At this early development stage, the cost of the Class 1 HDPE material is significantly greater than standard duct materials such as sheet metal and flex duct. CDC is exploring extruding as well as rotomolding processes to reduce the manufacturing cost. However, with process refinement and mass production of standard fitting shapes and sizes, the material costs should drop considerably.

The installation cost benefits are also difficult to assess at this early stage. The limited number of fittings currently available resulted in a less than optimal installation with extra joints and labor to install. Even so, the potential for reduced installation costs is apparent with the elimination of duct sealing labor and material.

Optimized Duct Sizes (Computational Fluid Dynamics Analysis)

One of the advantages that plastic ducts offer is the potential low pressure drop due to smooth branch take-offs, which can be easily incorporated into fabrication of plastic ducts. Computational Fluid Dynamics (CFD) modeling has been utilized to model flows in ducts. Mumma and Mahank[7] undertook a CFD study to model duct fitting resistance for different geometries. They modeled seven different fittings including a diverging fitting, SD5-12 (rectangular duct geometry). The agreement between CFD modeling results and the experimental pressure loss coefficients was quite good in some cases

[7] Mumma, S.S., and Mahank, T.A., "Determination of Duct Fittings Resistance by Numerical Analysis," Final Report submitted by Penn State University, ASHRAE Research Project 854, 1995.

and was not good in a few cases. Their general conclusion was that CFD can be useful in modeling duct fitting resistance. Therefore, SWA undertook a CFD modeling task for estimating the pressure drops due to branch take-offs in ducts of circular cross-section. Two simplified duct geometries were considered as shown in the following figure.

CFD2000, a general purpose computational fluid dynamics (CFD) modeling software developed by Adaptive Research, was utilized for performing duct simulations. CFD2000 is designed to solve numerically the Navier-Stokes equations, which are fundamental physical governing equations of mass, momentum and energy conservation for a fluid flow in a flow field. The program uses a finite-volume representation of the governing equations. The problem domain is divided into multiple control volumes and the governing equations are applied to those individual control volumes and integrated over the entire problem domain. The resulting algebraic equations are then solved using an efficient numerical method to obtain a solution of the engineering problem. The program is capable of solving laminar fluid flows and turbulent fluid flows as well.

Modeling in CFD2000 involves the following steps:

1. Building geometry (as shown in Fig. 2) is drawn and computational mesh (see Fig. 3) is generated as shown in Fig. 2 in CFD2000.

2. Problem type is selected – two-dimensional/three-dimensional, heat transfer and/or fluid flow, laminar or turbulent, chemical reaction

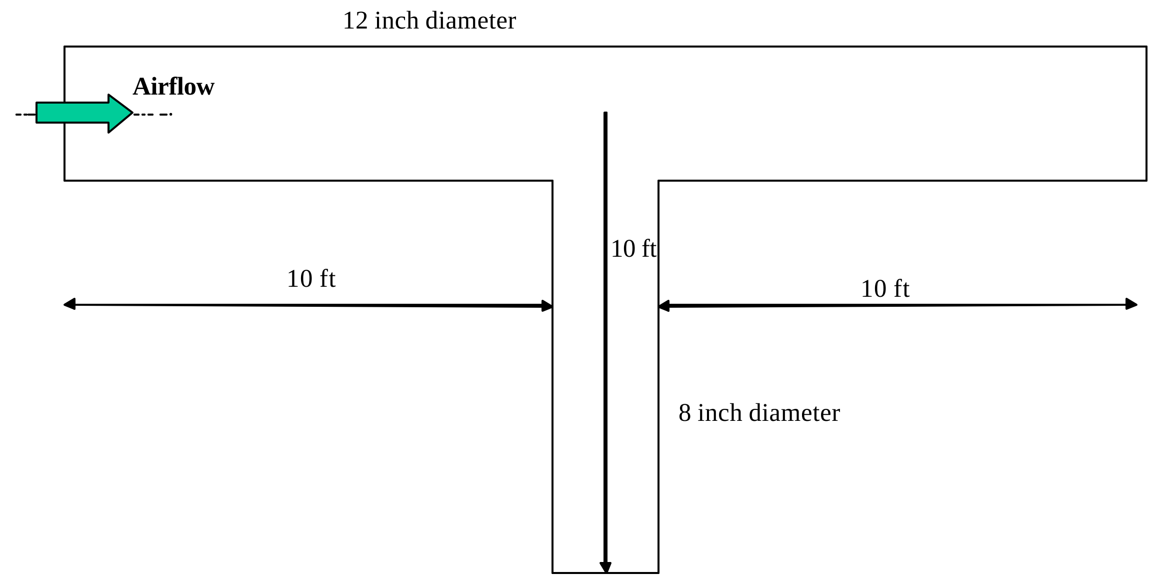
3. Fluid properties are then defined. CFD2000 has a database for commonly used fluids.

4. Boundary conditions are then specified. Boundary conditions include the specification of outer walls, flow inlets, flow outlets, inside blockages (interior walls), and body force.

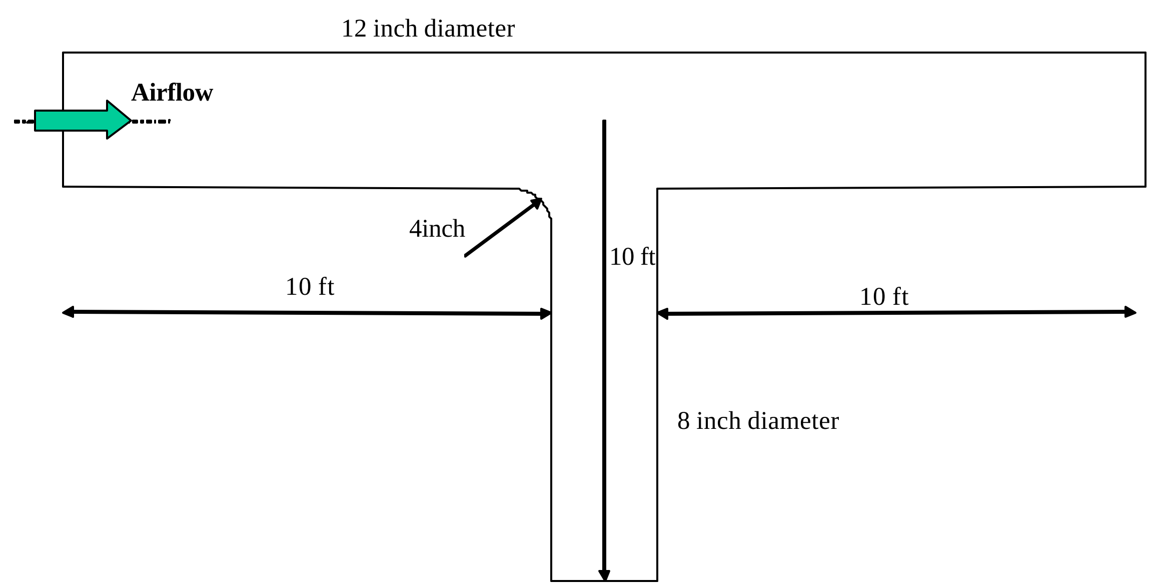
5. Solution control features such as initial field values for all variables, time-step, time of computation, and the desired output are selected.

6. Program is then executed and the results are graphically processed in Fieldview of CFD2000.

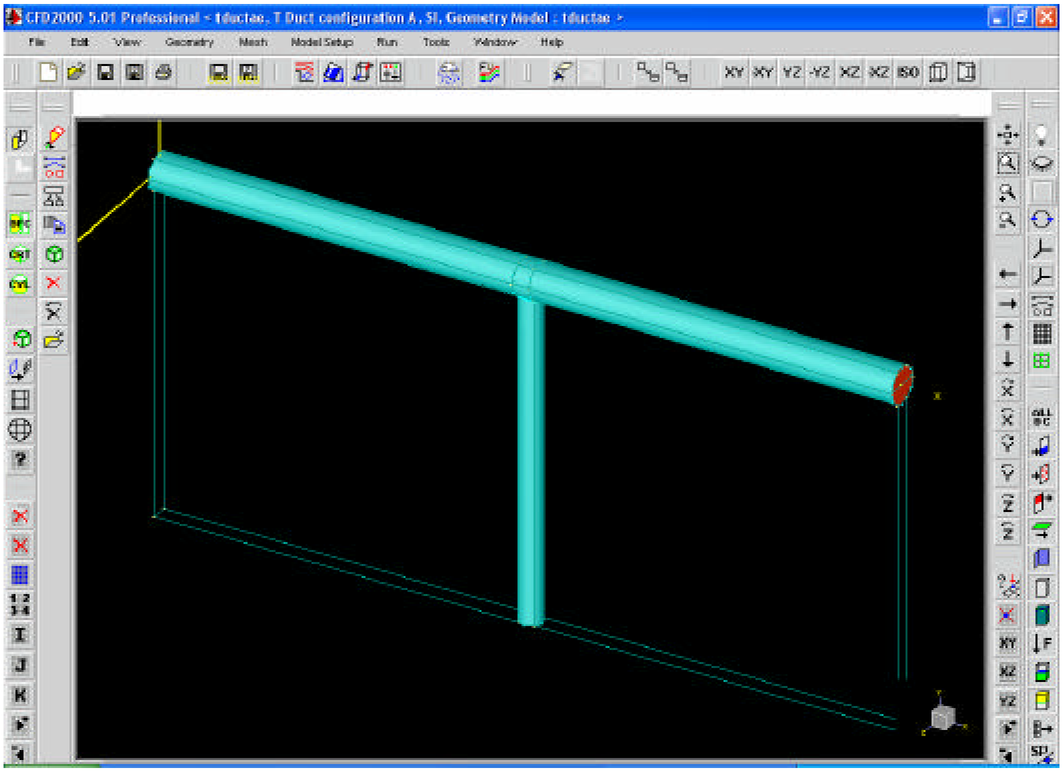
(a) Basecase



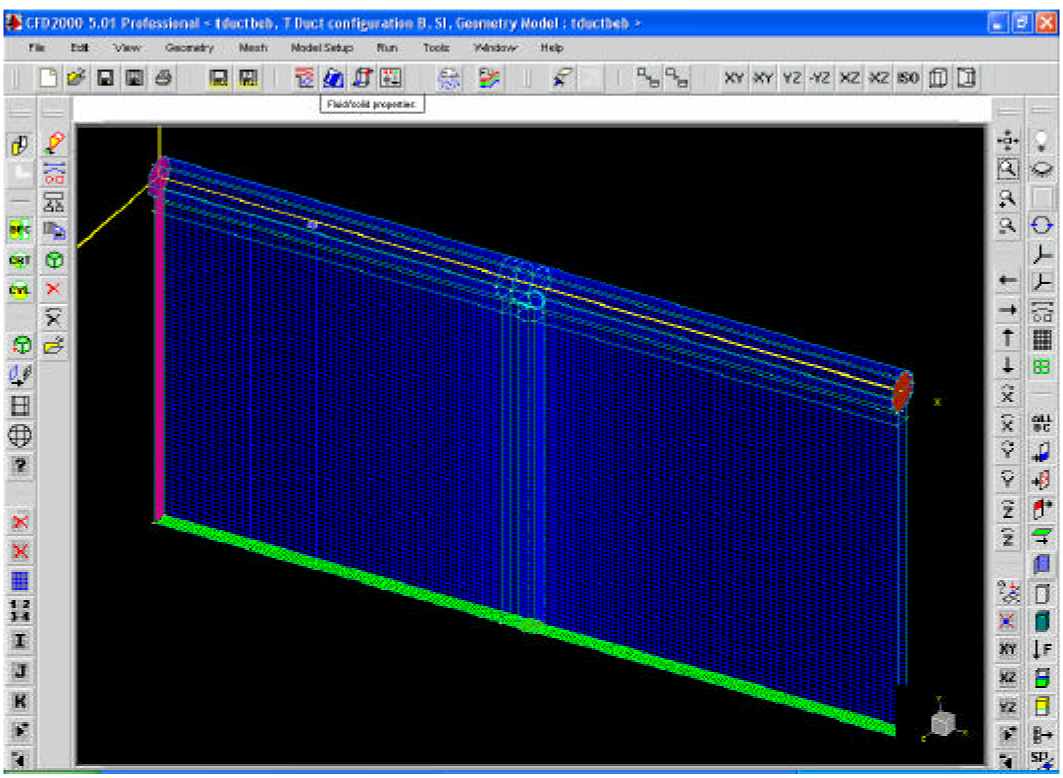
(b) Alternate 1 with Smooth Take-Off



Duct geometries utilized in CFD modeling of basecase (a) and alternate (b).



Duct model in the CFD2000 environment.



Duct model with mesh generated in the CFD2000 environment.

The following boundary conditions/assumptions were used in the CFD simulations:

Inlet velocity = 12.5 ft/s

Fluid -- Air at 80^{o}F

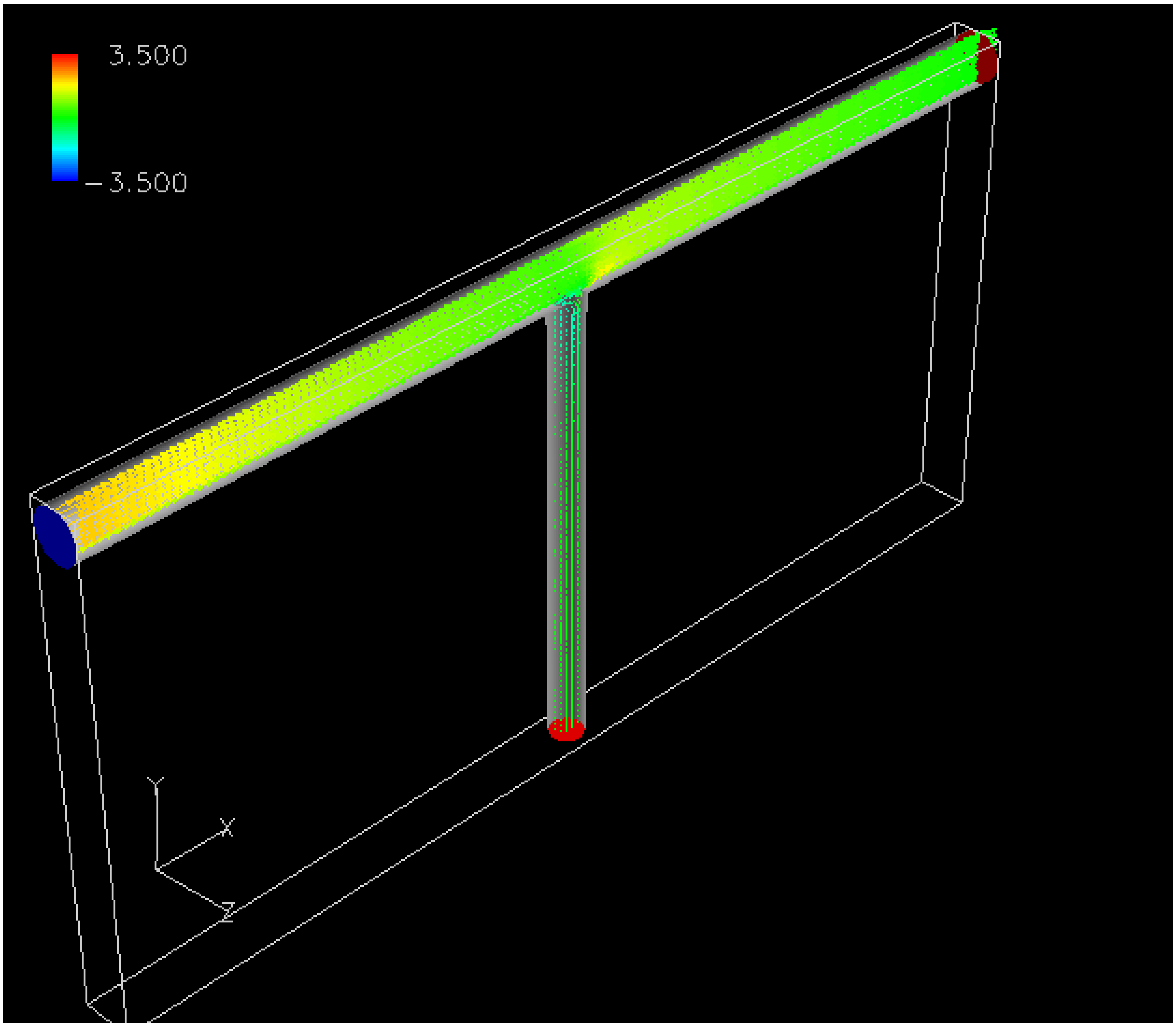
Flow type --Turbulent, Standard k-e model

Outlet Boundary condition – Specified pressure

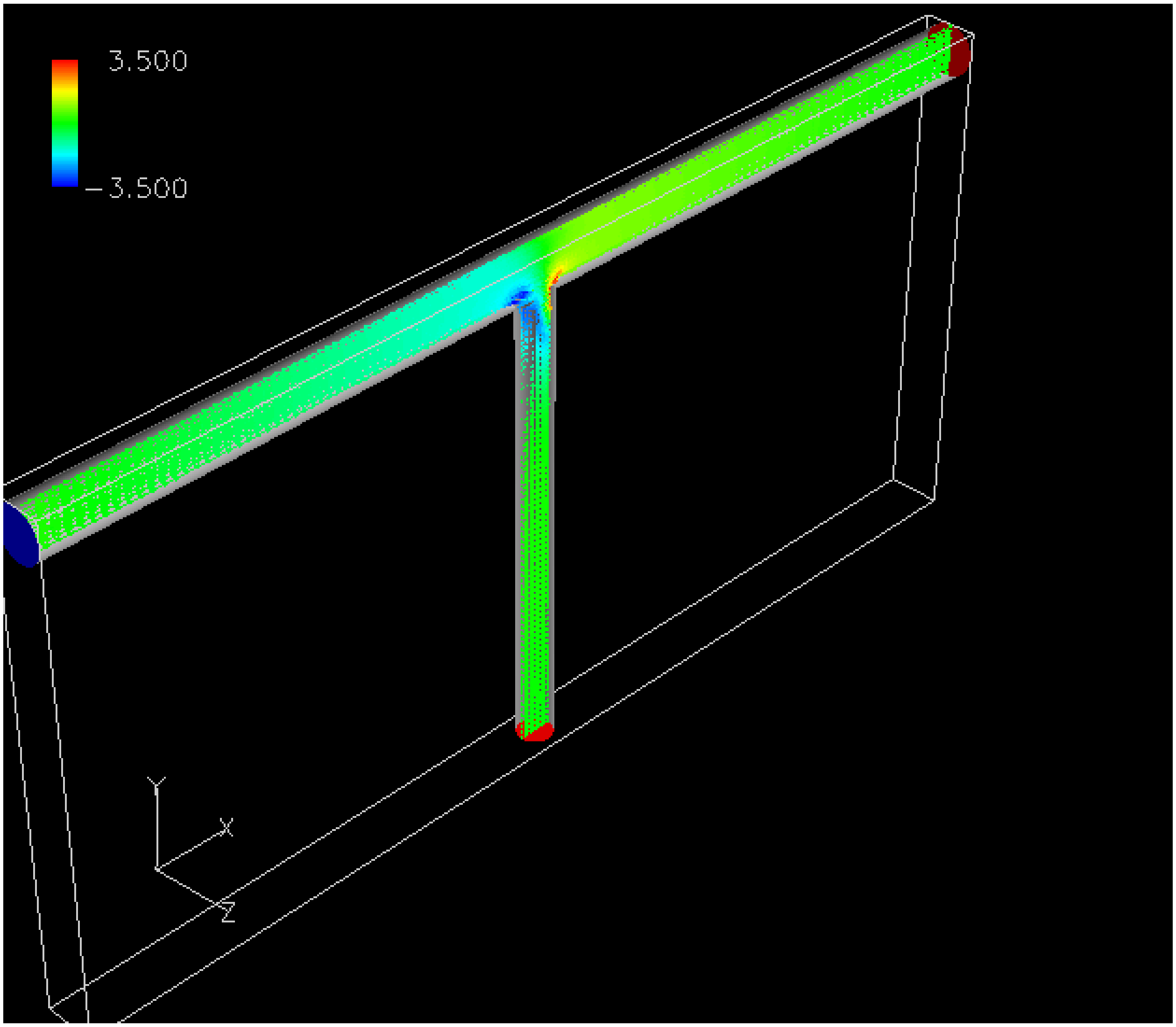
Total number of nodes in the computational domain --130,000

Mumma, et al. experienced significant difficulty in modeling SD5-12 geometry (branch take-off or diverging Tee) since the software used did not allow for multiple outlets. However, CFD2000 allows for multiple outlets. We selected the specified pressure boundary condition for the outlets assuming the pressure at the outlet approaches the room air pressure (set at zero).

Results for the CFD runs are shown in the following figures. The first figure shows velocity vectors with pressure contours (in color). The legend is for pressure. When the pressure is specified to be zero at the outlets, the steady state solution yields a pressure of 2.1 Pa at the inlet for the basecase (a, with sharp branch take-off). As shown, the flow velocity and hence the flow rate in the side branch is lower due to abrupt take-off. The second figure presents velocity vectors with pressure contours for the second case where the branch take-off is smooth. In this case, the inlet pressure reaches upon steady state a value of about 0.2 Pa. It can be inferred from these results that there is a net loss of about 2 Pa due to the abrupt branch take-off. This preliminary CFD analysis confirms that the smooth, rounded take-offs easily achievable with plastic ducts can produce significant reductions in pressure losses in the overall duct system.



CFD simulation results for the basecase (a), sharp edge take-off.



CFD simulation results for the alternate case (b), rounded edge take-off.

Additional Research Needs and Commercialization Plans

In the near-term, the QADUCT™ from CDC Enterprises represents the closest product to commercialization. However, SWA believes several improvements will be necessary for residential HVAC market success.

> Duct shape: HVAC duct systems in two-storey homes typically involve rectangular and/or oval ducts running through wall chases. Round ducts are not appropriate for this application. This is a significant market limitation. The large round trunk ducts also present head-room issues in basement installations. For successful commercialization, the product needs to move from a round cross-section configuration to a rectangular cross-section.
>
> Duct connections: A replacement for the gasket and clamp arrangement used by CDC Enterprises is needed. The width of the clamp impacts duct spacing, it is labor intensive, and it is expensive. SWA believes that a gasketed fitting system such as that shown in the following picture could be developed to be leak free under relatively low pressure conditions.

Gasketed sewer fittings.

> Proctor Engineering Group pursued a similar gasket concept for sheet metal ducts and developed the PEGIT duct connection system with SBIR funding.[8] SPIRAmir® uses a similar concept and is a commercially available product.
>
> Optimum fabrication process: Molds for rotomolding are less expensive than for blow molding. However, the inside surface of rotomolded parts is not smooth and wall thickness can vary. Blow molding can produce more intricate parts to more precise specifications, but the process of incorporating fire retardant additives needs further research. Thermoforming should also be revisited.

In terms of passing the “must meet” criteria identified earlier, the concept is not ready to proceed to the next stage of development, preproduction. The air leakage and fan energy performance benefits of plastic ducts are apparent. However, the round ducts do not readily integrate with current residential construction details. A code-approved

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[8] Iain S. Walker, Douglas E. Brenner, Max H. Sherman, and Darryl J. Dickerhoff, "Evaluation of PEGIT duct connection system", August 1, 2003, LBNL-43382.

plastic material is available, but the addition of flame retardant adds significant cost. The ultimate cost of the system has yet to be defined well enough to assess the marketability of plastic duct systems.

Long-term plans for commercialization should include action to initiate code language modifications that specifically address above-grade installation of plastic ducts. The American Plastics Council has demonstrated interest in this project and could potentially support a code modification effort. The justification for the Class 0 or 1 material classification requirement should also be researched further to determine if there is any opportunity to eliminate the requirement which adds significant cost to the product.

Appendix

Phase I Final Report

Preliminary QADUCT^{TM} **Brochure**

Truss-Integrated Thermoformed Ductwork

Final Report

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May 15, 2002

Prepared for

THE U.S. DEPARTMENT OF ENERGY
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1. SIGNIFICANCE, BACKGROUND INFORMATION, AND TECHNICAL APPROACH

1.1 Introduction and Summary

Steven Winter Associates, Inc. (SWA) undertook SBIR Phase I research and development to produce a leak-free residential duct system that is cost-effective and easy to install within the home's thermal envelope. The system uses thermoformed plastic ducts installed in a recessed roof truss underneath the attic insulation (and in other configurations). The potential benefits of this approach are many:

- Plastic ducts are potentially leak-free. Easy and effective methods for sealing plastic pipe are known. The problems with excessive air leakage in today's duct systems have been well documented.
- Ducts integrated into the recessed roof truss (Figure 1) are thermally isolated from the hot attic space by traditionally-applied roof insulation (R-19 to R-48). Today's ducts in attics are typically only insulated to R-4.2, some to R-6. There are limits to the amount of insulation that can be applied to ducts in terms of performance (as insulation is added, surface area is added) and handling and sealing practicality.
- Plastic ducts with smooth interior surfaces and curved take-offs and turns will have lower friction losses than typical flex duct, duct board or sheet metal systems. This may be translated into smaller duct sizes (less material cost) and/or reduced fan energy requirements (operating cost savings).
- Plastic thermoformed duct systems can be prefabricated to reduce the effort and skill level required in the field.
- Plastic ducts can be easily cleaned to alleviate health concerns over dirt accumulation and potential mold growth.

The Phase I research objectives have been met. Thermoformed plastic ducts can be produced economically (Figure 2) and they can be easily configured into a complete leak-free distribution system (Figure 3).

The focus of the Phase II effort will be on the duct system integrated with the recessed truss design, but many of the same benefits will also apply in conventional attic, basement, and crawlspace installations. Opportunities to make the system more universal in its application will not be overlooked. It is also proposed that the possibility of on-site thermoforming be researched to provide more field installation flexibility.

The Phase II research will focus on further improvements to the thermoforming process, additional material selection research, universal duct system component development, independent laboratory testing, and full-scale prototype field evaluation of the proposed truss-integrated systems.

The following shows the components of the proposed technology and some of the Phase I research accomplishments.

Figure 1 Recessed-configuration trusses in house designed by SWA for Mercedes Homes. The recesses allow for ductwork to be installed under the insulation layer, i.e., within the building's thermal envelope.

Figure 2 Thermoformed ductwork component, produced by SWA during Phase I research.

Figure 3 Assembled Phase I prototype duct system, all produced in two thermoforming molds. The system was virtually airtight.

1.2 Problem Identification and Significance

The problem is clearly identified and described in the SBIR Program Area Overview for Low-loss Thermal Distribution Systems: research has identified serious deficiencies associated with residential and other duct systems, including high duct leakage and inadequate duct insulation, combined with difficulties posed by installation constraints, flexibility needs, and cost and other considerations. Among the problems with residential thermal distribution systems, duct leakage is recognized as a monumental problem as illustrated to the right and listed in Table 1.

Residential Duct Leakage:

Costs the nation over $5 billion annually.

Energy equivalent to annual oil production from Arctic National Wildlife Refuge.

Equivalent to consumption of 13 million cars.

7 billion trees needed to offset the CO_2 emissions.

Reference: LBNL

Table 1 summarizes a number of studies on residential duct leakage and energy saving potential.

Table 1. Duct Leakage Studies

Study Author	State	Existing or New	Sample Size	Duct Leakage cfm25	Energy Saving Potential, %
Blasnik et al. [1]	NV	New	30	253	26
Blasnik et al. [2]	CA	New	10	292	25
Blasnik et al. [3]	AZ	New	22	193	11
Cummings et al. [4]	FL	Existing	24		18
Hammerlund et al [5]	CA	New	12		24
Hammerland et al. [5]	CA	New	66		6
Jump et al.[6]	CA	Existing	24		18
Katz et al.[7]	NC & SC	New	96	360	
Modera and Jump[8]	CA	Existing	3		19
Neme et al.[9]	MD	New	25	204	12
Palmiter and Francisco[10]	Northwest	Existing	22	287	16
Penn[11]	FL	Existing	10,620		17
Proctor[12]	CA	Existing	15	276	18
Proctor and Pernick[13]	CA	Existing	1,000	246	18
Proctor et al.[14]		Existing	30	397	
Proctor et al.[15]	NJ	New	52	299	20
Siegel et al.[16]	OR	Existing	8	241	16
Treidler and Modera[17]	MD		4		9
Vigil[18]	NC	Existing	82	188	13

SWA's earlier research has confirmed and quantified problems associated with residential air distribution systems in numerous instances. The company's research, design and testing work under DOE's Building America Program (Refs. 21-23), and under the multi-agency Partnership for Advancing Technology in Housing (PATH) program (Refs. 24, 25) has confirmed the following shortcomings in production-builder-installed air distribution systems.

○ Ductwork location	All across the South and Southwest, where cooling loads dominate and most homes have slab foundations, HVAC ducts are located in the attic, above the ceiling insulation, and penetrate the insulation to ceiling registers in rooms. This practice has moved North as well with the greater presence of central air conditioning. It makes sense to supply cool air at the ceiling, but running the ducts through the attic results in huge energy losses. For example, an attic in Phoenix is typically 140°F + every afternoon in the summer. Ducts with R-4 insulation carrying 55°F air are running throughout it. If the ductwork can be located under the ceiling insulation, energy consumption and peak demand can be decreased by a third or more (Ref 34).
○ Duct leakage	A January 2000 newsletter from DOE says: "Studies show that the ductwork in a typical new home loses between 20 and 30 percent of the cool air it carries in the summer" (Ref 26). This leakage can have significant negative impacts on system capacity, particularly at the most critical times, depending on duct configuration and location. Mastic and other leakage-reduction strategies are resisted by mechanical contractors because of added costs in material and labor time.
○ Duct insulation	Flexible ducts are the primary means of conditioned air delivery in attics and are typically only insulated to R-4.2. Greater levels of insulation are bulky and awkward to handle and even more difficult to seal. Insulation levels are further degraded by tight bends, "squeezed" ductwork and damaged insulation. Rigid ductwork is used less. It has insulation of R-2 to R-6, if it has any, and is even more constrained by geometry, installation pathways and damage in residential applications.
○ Duct sizing and length	Flexible and rigid ductwork is typically available in standard sizes, such as 6" diameter, 8" diameter, etc., and the near-enough-is-good-enough procedure for sizing and layout by mechanical subcontractors results in uneven air flows, poor pressure balances and system inefficiencies. If duct/register sizing and pathways could be optimized, without impairing installation cost or efficiency, overall performance could be enhanced by 15% to 20%.

Addressing these problems and their associated energy inefficiencies are the opportunity for innovative research conducted by SWA under Phase I and proposed for continued research under Phase II.

It is essential to understand residential HVAC duct distribution systems in order to fully appreciate the potential opportunity identified here. Figures 4 and 5 illustrate residential ductwork and interaction with various parts of the house and the outdoor ambient environment. Predominantly, HVAC equipment and ducts are placed in attics, basements, crawlspaces, garages and other unconditioned spaces. Ducts invariably leak to and from outside. Because of this leakage, we are not only losing heated or cooled air to the outside on the supply side, but also heating or cooling outside air that leaks into the duct system on the return side. In addition, ducts placed outside the conditioned space, lose or gain heat to the outdoor ambient environment through heat conduction and radiation.

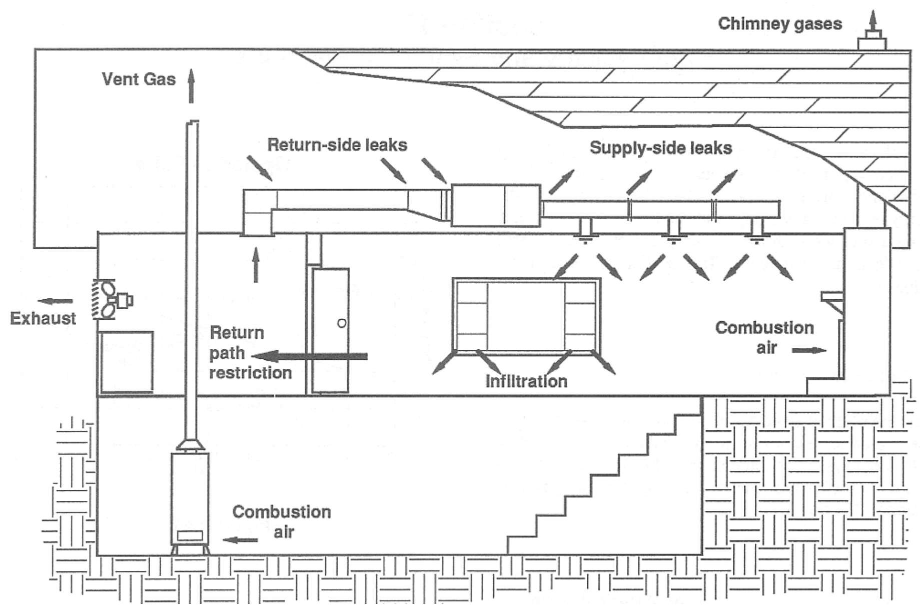


Figure 4 Air Distribution System in Residence

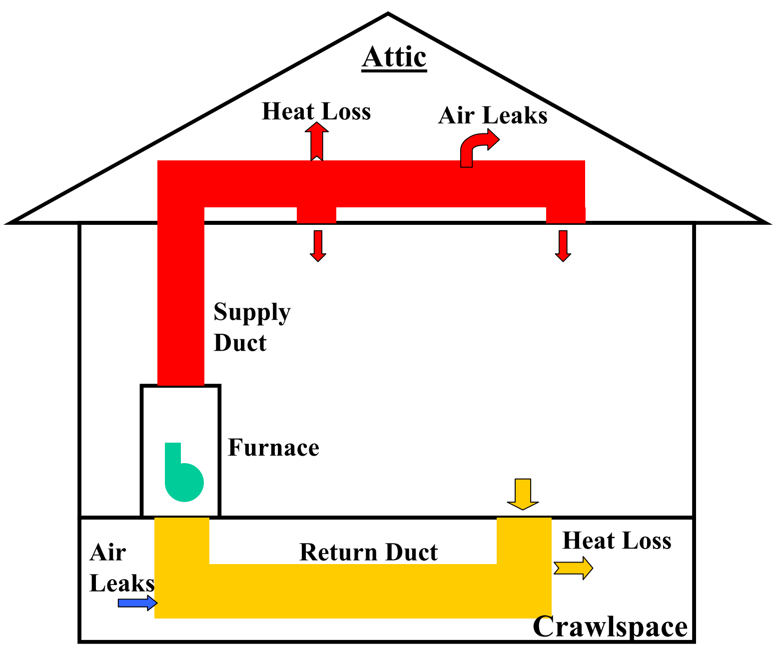


Figure 5 Duct Leakage and Heat Loss

Ducts leak at the numerous connections. Connections are typically achieved by screwed metal connections and duct tape. LBNL researchers have found that many duct tapes peel off duct systems leaving the system open to leaks (see Fig. 6). Duct tape and associated duct leakage are so serious that LBNL researchers have put together humorous publicity "bits" to attract the attention of the building industry. An example is cited below:

Figure 6 Duct Tape Peeling

Meanwhile, On Jeopardy

Fans of the TV quiz-show "Jeopardy" know that questions are phrased as answers and answers as questions. Last week in Baltimore, DOE's John Talbott caught an episode in which the question was "This material was identified by California researchers as effective for house-hold repairs – except for sealing air ducts."

Talbott reports, "The contestant correctly responded, 'What is duct tape?'"

Those California researchers are, of course, Berkeley Lab's own Max Sherman and Ian Walker of EETD.

LBNL has developed and commercialized a new technology to seal duct leaks "from the inside." Even though this technology offers the potential to reduce duct leakage (it doesn't, however, seal larger openings or cracks). The fundamental concept of the this research is to build better ducts that don't leak to start with and to avoid placing them in unconditioned spaces.

1.3 Technical Approach

For Phase I research, SWA identified a unique opportunity to develop a new class of ductwork for residential applications that brings together two families of technologies that have not been combined in the past – **an innovative roof truss technology and thermoformed ducts.**

The **innovative roof truss technology** is a coffered- or recessed-ceiling configuration (Figs. 7, 8) that accommodates the air distribution system, while permitting the entire layer of ceiling insulation to be installed over it.

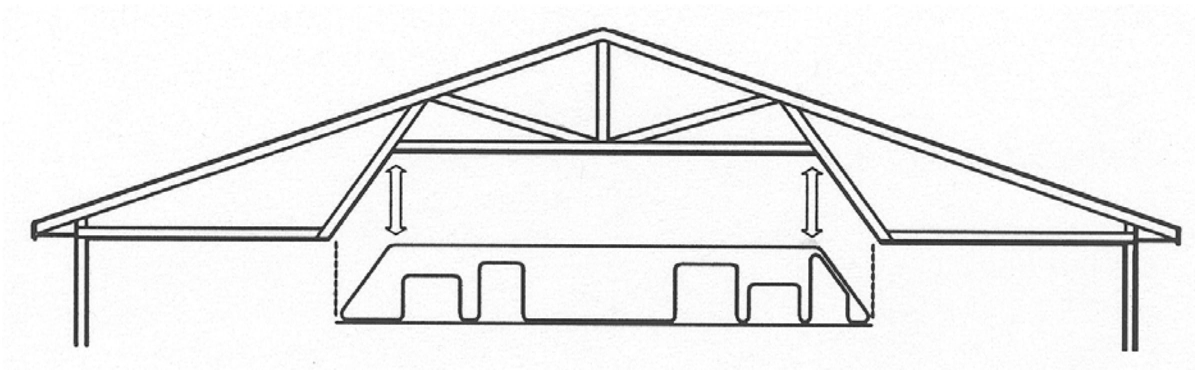


Figure 7 Coffered-ceiling roof trusses (from Phase I proposal)

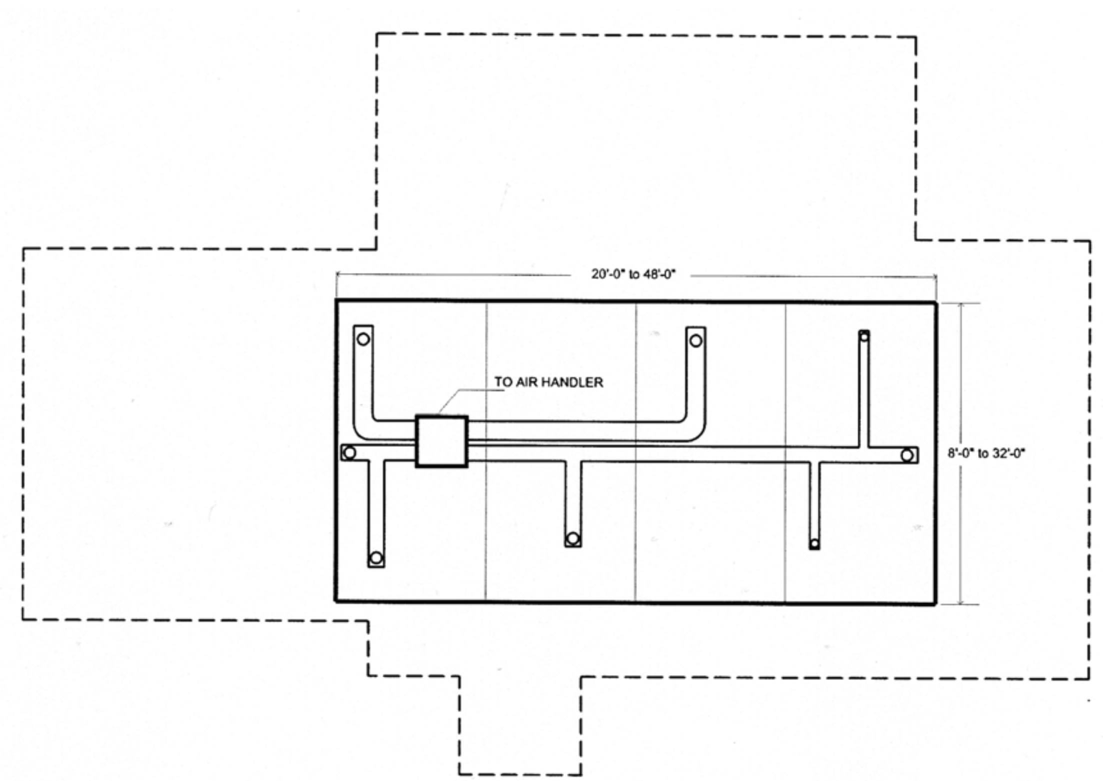


Figure 8 Sample house plan with CAD-designed ductwork array for ceiling truss integration (from Phase I proposal)

Wooden roof trusses have been used in the construction industry for more than a thousand years. A major leap forward in their efficiency took place in 1952 with the invention of the metal connector plate by Calvin Jureit (Ref. 27). This allowed for the use of truss chords made of small-dimensional lumber (2"x3", 2"x4", etc.) which are very efficient by virtue of their structural connection using metal plates. Computer programs routinely design trusses for every conceivable roof shape required (including variations in roof configurations for slopes, shapes and indents of all kinds), specifying the lumber dimension and connector plate configuration required for its structural stability.

Figure 9 Recessed-configuration trusses in house designed by SWA for Mercedes Homes

As a part of its ongoing systems-engineering research and demonstration work under DOE's Building America Program, SWA has been working very closely with Mercedes Homes of Melbourne, FL (the 38th largest builder in the U.S. with 1998 production of 1,630 homes), and its subsidiary, Space Coast Truss of Cocoa, FL (the largest producer of wood-framed residential roof trusses in Florida). In early 2000, SWA and Mercedes developed the recessed ductwork configuration for roof trusses shown in one of Mercedes' homes in Figure 9.

The ceiling insulation in the house turns up and runs across the top of the ductwork, so the ductwork is completely within the thermal envelope (see Figures 10 & 11).

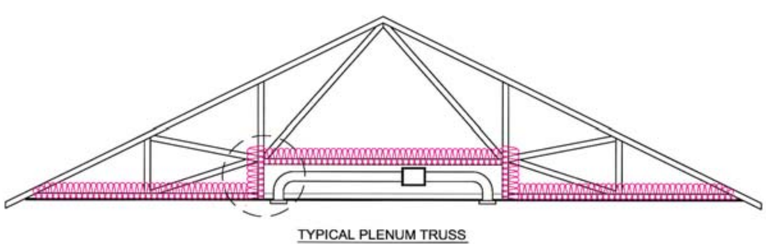


Figure 10 Insulation detail shown installed over ductwork in Mercedes' recessed trusses

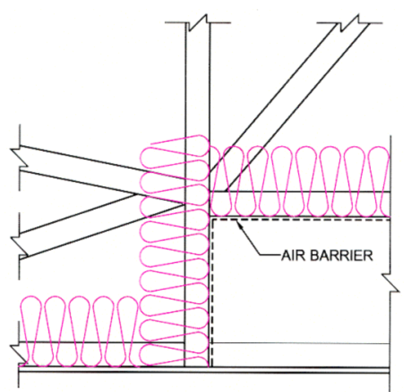


Figure 11 Recessed truss detail

Cost analyses conducted by Mercedes and Space Coast proved the cost viability of the system, and the Mercedes/SWA team redesigned six of the builder's house models to accommodate the truss-integrated ductwork system. The six prototype homes using the truss-integrated recessed ductwork system shown above were built by Mercedes in mid-2000, and subsequently tested by SWA in conjunction with the National Renewable Energy Laboratory for energy efficiency. More development is currently ongoing to further explore recessed-truss techniques. The company has deemed this SWA-led innovation as one of its best in years, and the Building America program has benefitted from valuable outreach and feedback in the media (Ref 28).

While the truss system design, production and erection have posed no problems, technical or otherwise, the installation of the ductwork identified several opportunities for significant improvement. Subcontractors can lift and install ceiling ducts to the underside of trusses (versus working high up between the truss chords in conventional roofs), but working with many individual ductwork sections, dealing with numerous bends, joints and connections, sealing leaks in almost-inaccessible spaces, and other conditions arising from the design, all point to the need for further innovation.

Thermoforming technology is used to manufacture modular air-delivery array from light-weight thermoformed plastic (Figs 12, 13). The transportable modular components can be easily assembled on site into the final array. The array is lifted and installed into the recessed-ceiling section of the roof trusses.

SWA's Phase I proposal called for the recessed-ceiling truss configurations cited above. However, the results of Phase I research have shown that thermoforming technology can result in leak-free ducts that can be located anywhere that conventional ducts are placed, in addition to being suitable for recessed trusses. In addition, Phase I research has determined that it is possible to carry out thermoforming on site economically. This flexibility allows for installation of thermoformed ductwork on site to any configuration, and greatly enhances the potential commercial success of the research effort.

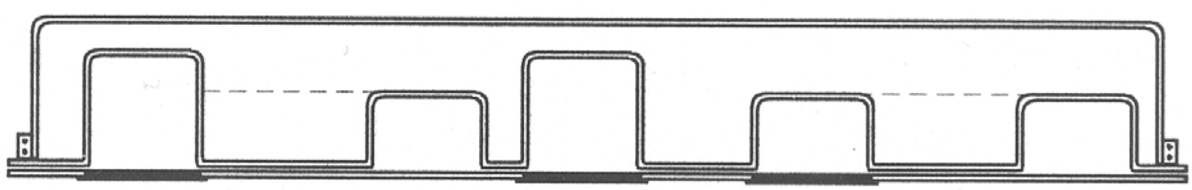


Figure 12 Section through thermoformed duct tray *(from Phase I proposal)*

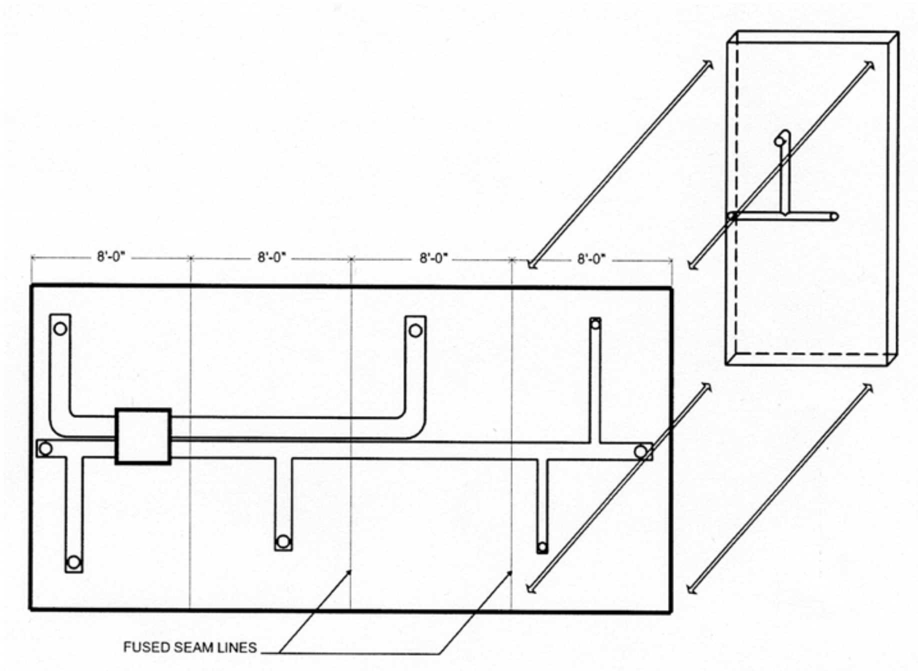


Figure 13 Plan View of 8'-wide duct tray sections, fused together to form 16'-wide x 40'- long ductwork array to be integrated into ceiling *(from Phase 1 proposal)*

Although we know of no prior inventions encompassing the proposed technology, a search of patent applications revealed one concept similar in principle to ours. Figure 14 below (U.S. Patent 6,086,145 issued in 2000, Ref 29) represents an automotive headliner assembly that has integral air-supply ducts and receptacles for electrical wiring. This is achieved by blow-molding, a plastic manufacturing process.

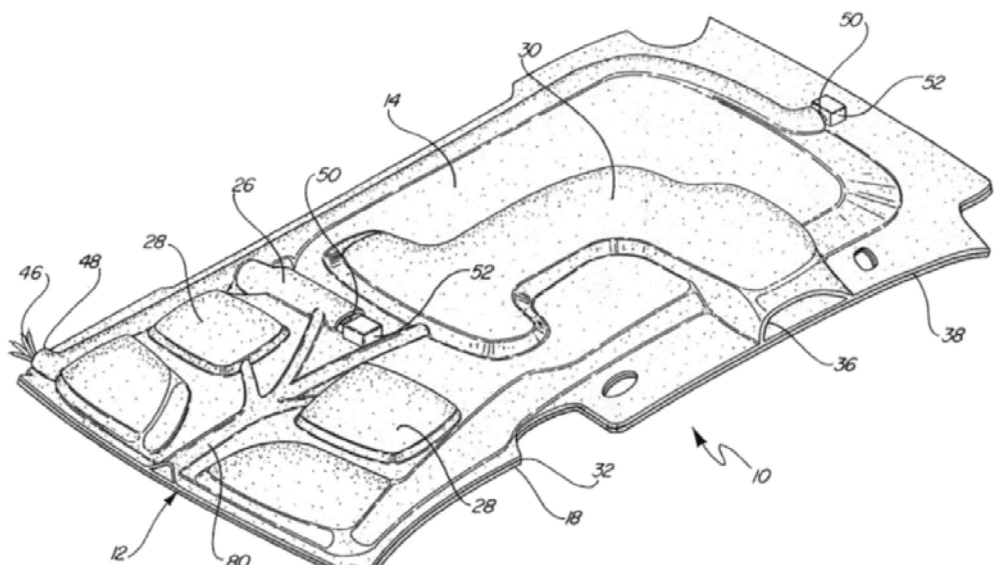


Figure 14 Automotive headliner assembly concept with integrated air and wiring ductwork, molded as a one-piece array *(Phase I proposal)*

Thermoforming, the technique proposed to fabricate ductwork arrays, is a generic term for the processes of manufacturing plastic products from sheet plastic (Refs. 30, 31). Basic facts about thermoforming:

1. Estimated North American market for thermoforming is $15 billion
2. Typical industrial thermoformed products include:
   Cabinets for medical and electronic equipment, transport trays, automotive inner-liners, headliners, instrument panel skins, aircraft cabin wall panels, bathtubs, food-serving trays, packaging materials, etc.
3. Some of the processes under thermoforming include vacuum forming, pressure forming, and twin sheet forming.

Thermoforming involves heating the plastic sheet to a temperature where it is soft, and then stretching the softened sheet against a cold mold surface. When the sheet has cooled and retains the mold shape, it is removed from the mold and the excess plastic is trimmed. These processes are shown in Fig. 15.

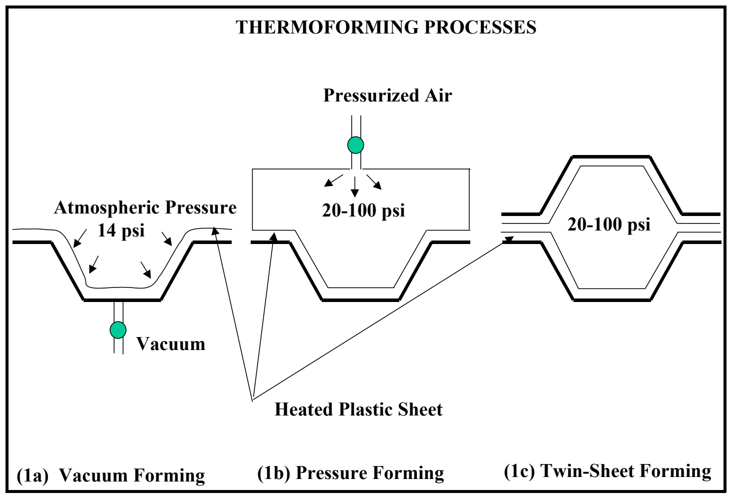


Figure 15 Schematics of Thermoforming Processes

In vacuum forming (shown schematically in 1a of Fig. 15), the heated plastic sheet is stretched to conform to the shape of the mold by creating a vacuum beneath the plastic sheet, which then causes the atmospheric pressure (14 psi) to push the sheet down into the mold. In pressure forming, compressed air at pressures much higher than atmospheric pressure are used, which ensures sharp and precise corner and edge details of the part. In twin-sheet forming, two parts can be vacuum formed separately or simultaneously and then bonded together using either adhesive bonding or thermal bonding to form an enclosed part.

Even though vacuum forming is not a continuous process like extrusion, it approaches a continuous process with automation. For thin gauge parts, sheet plastic can be fed from a roller (6 ft diameter and 6000 lbs of plastic) to an automated process that heats the plastic sheet, vacuum forms the part, punches and stacks the parts all in-line (see Figs. 16, 17). For heavy gauge parts, sheets are fed one by one.

Figure 16 A photograph of a roll-fed thermoformer

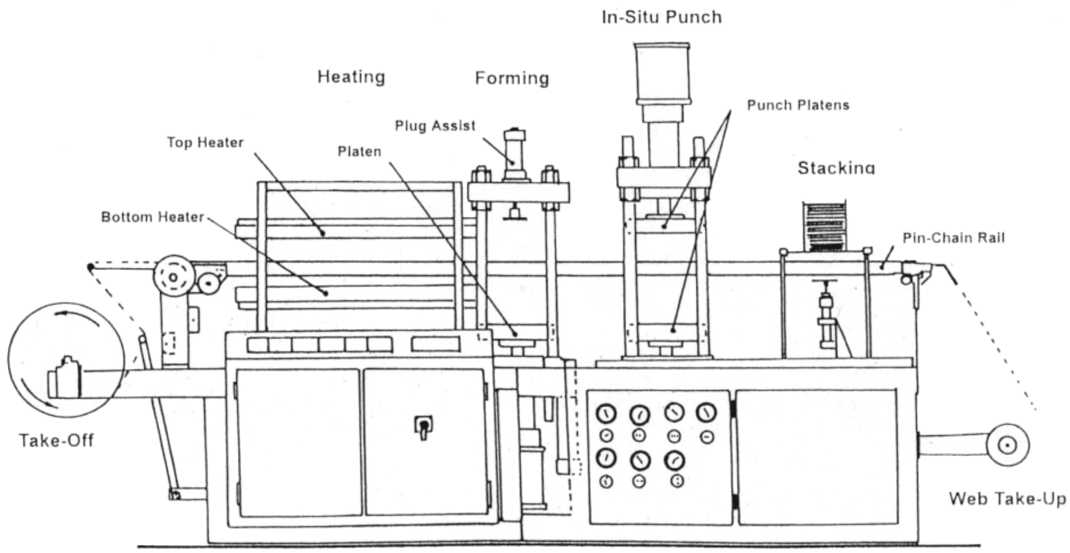


Figure 17 A schematic of a roll-fed thermoformer

For manufacturing ducts for residential application, we believed that vacuum forming would be adequate for the low-cost, large-scale applications being proposed, depending upon the thicknesses required and the complexity of the shape, both of which are subjects of the proposed continuing research. Twin sheet forming can also be employed for providing complete ducts.

Key components of vacuum forming equipment are heating system, vacuum system, and the mold. For our application, the most critical element is the development of a flexible-use, cost-effective mold system. Since there are multiple configurations of duct systems, just one mold will not be adequate. The ability to rapidly form various mold configurations will determine whether this process is suitable for forming ducts or not. We believe that modular molds can be made and arranged such that numerous duct configurations can be produced.

Current mold materials include wood, epoxy, aluminum, and ceramic. Aluminum molds are typically used for production runs while other molds are used for prototype runs. Mold making technology is very mature with the advent of CAD/CAM and CNC technologies. As with the choice of material, cost of the mold will be a primary consideration in the continued research under Phase II.

Some of today's thermoformers have the capability to produce components measuring 20 ft by 30ft with thicknesses ranging from 0.010 inch to 0.5 inch (and beyond). It appears that it is feasible to produce large size integral ducts with thermoforming. Theoretically, there is no limit to the size that can be thermoformed, but there are practical limitations on how large the oven (heater) is and how large the plastic sheet is. However, this equipment can be custom designed and built to required specifications. We, therefore, believe that low-cost, large-scale thermoforming can be developed and is well-suited for the proposed application and the proposed research will characterize the process best suited for the duct system.

As indicated in Section 3, Phase I research has been a success, and SWA researched, designed and produced a full-size section of virtually leakproof thermoformed ductwork.

2. ANTICIPATED BENEFITS

2.1 Energy

The primary benefit of the truss-integrated thermoformed ductwork system is that it will significantly reduce energy consumption and peak summer electric demand by solving the shortcomings in conventional ductwork construction outlined in 1.2 above. This is accomplished by:

- Thermally isolating the ductwork, via the recessed truss, from the temperature extremes of the attic. This not only reduces energy consumption, but impacts the system capacity required because the thermal gain penalty is highest at peak design conditions.

- Virtually eliminating duct leakage by having fewer connections and proven sealing methods. This provides another opportunity to downsize the equipment by eliminating the leakage component of the system load.

- Reducing duct system friction losses with a smooth interior surface and rounded turns and take-offs. This results in reduced fan energy requirements.

SWA's research has shown that eliminating duct leakage and moving the duct system out of the attic can reduce energy use by 15% to 20% in a single-family home, or up to 4MWh per home (national average).

DOE suggests in a January 2001 report, that the design cooling load can be reduced by one third (Ref 35). SWA has demonstrated in several Building America prototype homes reductions of one to two tons on modestly sized homes (Ref 36).

If 20% of the nation's newly constructed homes employed this system, resultant electrical savings would be approximately 1.3 billion Watt-hours for homes built in a single year, or a cumulative total of 36 billion Watt-hours over 7 years.

2.2 Labor and Material Costs

The proposed Phase II research will confirm the cost/benefits of the innovation, but it is expected to yield significant construction cost savings because:

- Much of the ductwork system can be prefabricated to reduce the effort and skill level required in the field.

- A thermoformed plastic ductwork system, which needs no insulation of its own, versus many insulated metal and plastic ducts connected with fasteners and sealed with mastic or adhesive tape, will result in reduced material costs, as well as reduced costs for scrap and trash removal.

2.3 Other Benefits

Ancillary benefits of the proposed system include:

- Better humidity control with a smaller sized air conditioning system that is better matched to the typical load rather than sized to meet an extreme peak design load

- Indoor air quality improvements due to:

  a) reduced impurities entering ductwork system because of fewer leaks,
  b) reduced air leaks from attic because ceiling insulation is not penetrated by ducts
  c) no fibrous material, as found with duct board, that can accumulate dirt and provide an opportunity for mold growth

- Reduced builder impediments as the truss-integrated design results in no dropped soffits or ceilings

3. THE PHASE I PROJECT

3.1 Technical Objectives

The technical objectives of the Phase I effort consisted of achieving proof-of-concept in two key areas:

1. Design and specification of the series of one-piece ductwork arrays suitable for incorporation in as many house plans and configurations as possible.

2. Selection of the specifications and performance characteristics of the thermoformed plastics to be used to form the ductwork trays for each house. These characteristics were to exhibit the needed strength, formability, health and fire-resistant properties. The work was also to verify that the selected material can be cut and glued effectively and that its surface characteristics will permit efficient air flow. Finally, the likely cost effectiveness of the system was to be determined.

These objectives have been successfully met, as outlined in the following section.

3.2 Phase I Research Findings

The results of the Phase I research and development tasks are summarized as follows:

Task 1. Review of Relevant Technologies

The use of plastics for ductwork is not new. The 2000 ASHRAE HVAC Systems and Equipment Handbook [19] provides a section on plastic ducts in Chapter 16. Fiber reinforced thermoset plastic ducts used for commercial and industrial applications are described in the "Thermoset FRP Duct Construction Manual" by SMACNA. Thermoplastic ducts such as polyvinyl chloride (PVC) ducts are described in "Thermoplastic Duct (PVC) Construction Manual" by SMACNA. PVC coated steel ducts and PVC ducts are used for the construction of underground air ducts since they offer corrosion resistance. SWA has worked with Cambridge Homes, in the Chicago area, under DOE's Building America program. Typically, this builder and others in the area employ underground PVC ductwork as shown in Figs. 18 and 19.

The round PVC ducts used for underground applications as shown are manufactured by the extrusion method. The main limitation of extrusion is that one can only produce uniform-cross-section products. Ducts with integral branches or connections cannot be manufactured. This can be seen in Figure 19, where boots are mechanically fastened, creating locations for air leakage. Duct Blaster testing confirmed that these systems had substantial air leakage.

The fact that PVC plastic ducts are already used for ductwork is encouraging to this Phase II research since most issues related to plastics, such as flammability and ability to withstand high temperatures, have already been satisfactorily addressed.

Figure 18 Underground PVC ductwork (extruded) for Cambridge Homes, Chicago's largest homebuilder.

Figure 19 Underground PVC ductwork showing mechanical fastening of boot, often a source of leaks. Note the procedure for duct diameter reductions: transfer sections with taped joints, also subject to leaks.

Task 2. Design Duct Array Configurations

The second task under Phase I was to conduct a research and design exercise to verify that most house plan layouts can be served by a ductwork system that can be economically produced. House designs frequently result in complex and non-rectangular "footprints", which may call for ductwork layouts that are less economical due to difficult geometries.

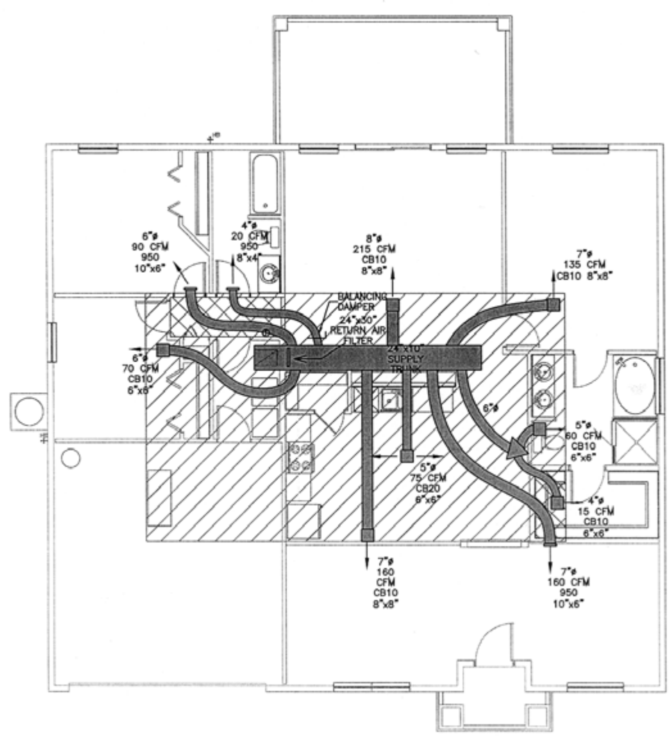


Figure 20 Rectangular recessed ductwork (shaded) enclosure in typical Mercedes Homes house

Initial indications were that most floor plans could be served by ductwork fitting into simplified rectangular shapes. This had been verified when SWA was working on the Mercedes Homes recessed-truss ductwork configurations. Figure 20 illustrates a rectangular plan of 1,813 sq. ft., for which a 20ft x 34ft recessed rectangular section (shown shaded) accommodated ductwork supplying all areas of the house.

SWA's Phase I research determined that a preferred approach to thermoforming the ductwork is to form a limited number of standardized duct system components that can be connected into configurations more similar to conventional duct layouts. The initially proposed design of a one-piece array involved significant amounts of sheet material that did not carry or transfer air. This not only constituted unresourceful use of materials and extra cost, but also added to the overall weight of the duct system.

Figure 21 shows a thermoformed duct component fabricated during the Phase I research. With this approach, the non-functioning sheet material can be trimmed off and recycled.

Moving to the modular component from the one-piece array also negates the need to have rectangular spaces and makes the thermoformed duct system more universal in application. The plastic ducts can be used in basements and crawlspace applications as well as attics.

Figure 21 Thermoformed ductwork component

During Phase I, SWA reviewed various residential duct configurations. Schematics of different duct systems employed are shown in Figs. 22 through 25.

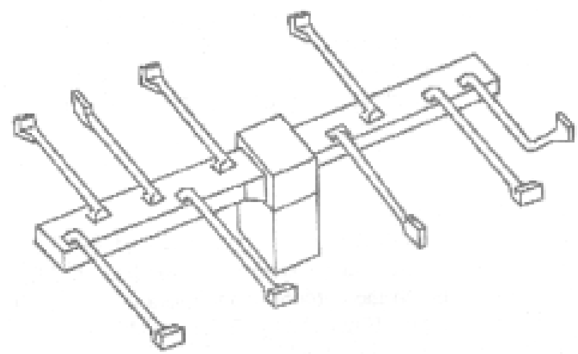


Figure 22 An extended plenum duct system

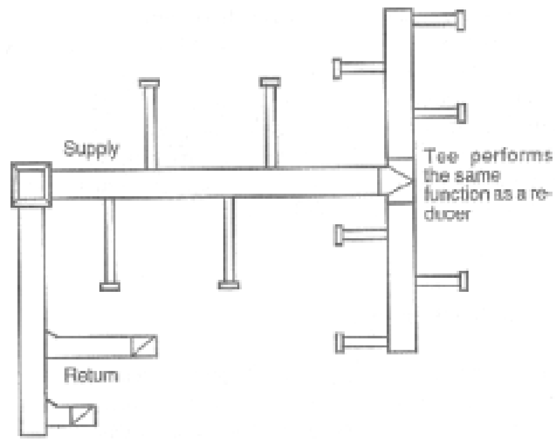


Figure 23 A variation of trunk and branch duct system

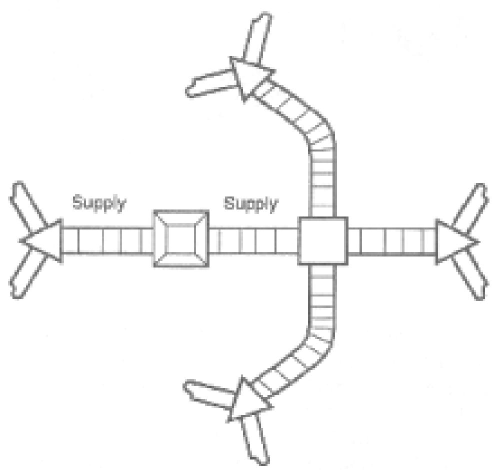


Figure 24 A flexible duct system

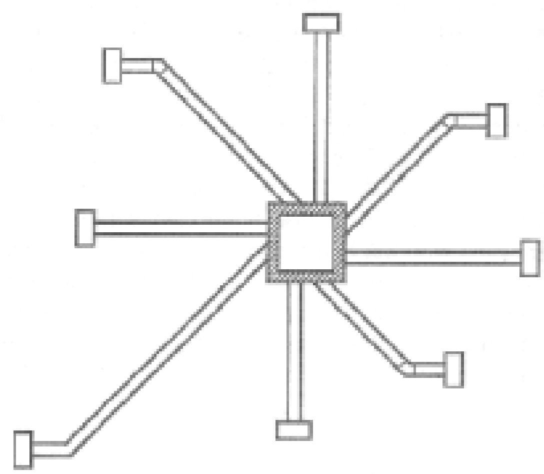


Figure 25 A radial duct system

SWA's Phase I research has determined that any of the above duct systems or combination of systems is feasible with thermoformed ducts.

Task 3. Research Thermoforming Technologies

The primary challenge of this Phase I task was to identify the candidate thermoformable plastic material. There are two general categories of plastics (or polymers) -- thermoplastics and thermosets. When a plastic can be heated and shaped many times without substantial change to its characteristics, it is a thermoplastic. When a plastic cannot be reshaped after being heated and shaped the first time, it is a thermoset. One of the key properties of thermoformable plastics is the "glass transition temperature." It is the temperature at which the plastic reaches a rubbery state when heated. Glass transition temperatures for thermoformable plastics are shown in Table 2.

Table 2. Glass Transition Temperatures for Thermoformable Plastics

Plastic	Glass Transition Temperature, °F
Polystyrene	200
PMMA	212
PMMA/PVC	221
ABS	190-248
Polycarbonate	300
Rigid PVC	170

Of the plastics listed in Table 2, PVC was considered by SWA for evaluation since it is already used for ductwork. PVC is one of the most versatile thermoplastics in use today. Type I PVC (rigid PVC) has excellent properties. It is self extinguishing and has a UL 94 VO rating. In addition, it offers good chemical and corrosion resistance. It is typically extruded and somewhat difficult to thermoform. However, when PVC is blended with other polymers, its properties are enhanced. As seen in Table 2, it had a somewhat lower glass transition temperature, indicating that it has a lower operating temperature. The primary limitation of PVC is the recommended environmental temperature limit of approximately 140°F. Yet, PVC is used for underground heated ducts, where temperatures could easily reach the recommended temperature limit. Another variation of PVC is CPVC which is capable of withstanding a temperature of 210°F. However, CPVC is more expensive than PVC.

Other materials listed above do not have self-extinguishing properties as good as that of PVC. However, some of them can be made fire retardant by blending with appropriate additives.

Fire retardant ABS is considered one of the alternatives to PVC if operating temperature is a concern.

An acrylic PMMA/PVC blend is considered an excellent alternative to PVC since it has all the requisite characteristics of PVC and exceeds PVC in terms of thermoformability and operating temperature. It is slightly more expensive than PVC but is less expensive than fire-retardant ABS. Therefore, we have identified acrylic/PVC as one of the candidate materials for thermoformed ductwork and in Phase I testing used a commercial material, ROYALITE R52. It is a fire-rated rigid acrylic/PVC product that combines very high impact strength, tensile strength, stiffness and hardness with excellent formability. It has a flammability rating of UL 94 VO. With conventional plastic fabricating tools, it is possible to machine, saw, drill, rout and grind this product. It can be joined by adhesive bonding, ultrasonic welding, and by mechanical fasteners.

Task 4. Prototype Development

Duct Design

SWA proposed in the Phase I Statement of Work to fabricate a bench-top model of ductwork. However, SWA elected to build a section of a duct system at full-scale to more clearly illustrate the concept's performance characteristics.

A duct system was designed that had realistic dimensions and yet complicated shapes to demonstrate thermoforming capabilities. An important consideration in designing the ductwork was to keep the number of molds required for forming at a minimum and to achieve a complex geometry to show the significance of thermoforming compared to extrusion or any other plastic manufacturing process.

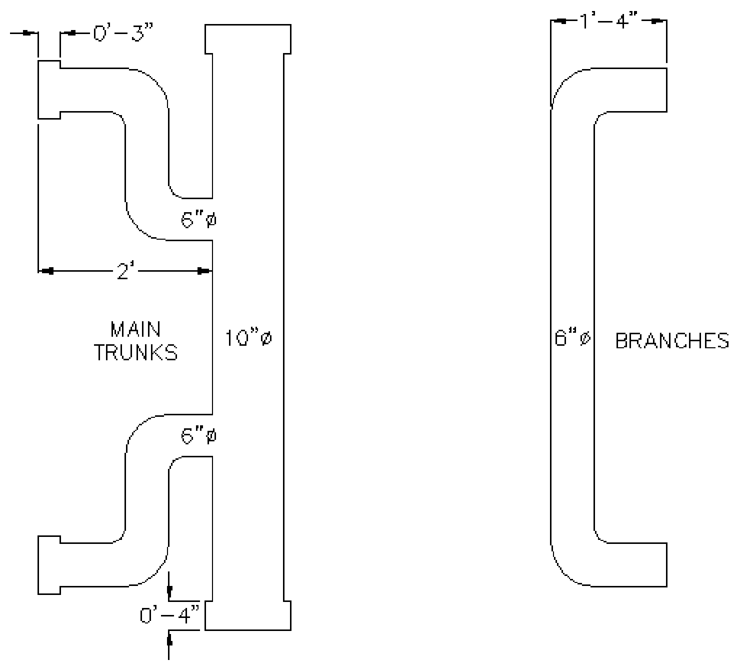


Figure 26 Geometry of prototype duct components designed and fabricated during Phase I research

Figure 26 shows the diagrams of duct components with which several different variations of ductwork arrays could be assembled easily. A diameter of 10 inches for the main trunk represents a realistic size. Branches of 6" diameter connect to the main trunk. These were designed to have 90º bends to provide out-of-plane branches by rotating the main trunk by 90º. If these bends are cut off, they can go straight from the main trunk. In practice the 90° bends could easily be 45° or any other angle to optimize air flows and to suit building geometries. **Such angular connections between branches of dissimilar size are very difficult to achieve effectively in conventional ductwork, but are extremely easy with thermoforming.**

Mold Fabrication

In thermoforming, the actual shaping and forming of the heated thermoplastic sheet is accomplished with molds. The heated and softened sheet is forced or drawn over a mold, and the shape of the mold is transferred to the sheet. The mold is the determining factor in the final shape of the formed plastic. There are three basic types of mold: female, male, and matched. Each mold type will have distinctive characteristics implanted into the formed part. A mold made with a cavity is called a female mold. A male mold is the opposite of the female mold – it has a protrusion instead of a cavity. In the third category, there is both a female and a male mold that are matched. The plastic sheet is clamped onto the female mold and the male is forced into the female mold. For the Phase I research, we selected a male mold for building the prototype, because it is easier to fabricate. Typically, production materials are aluminum alloys, ceramics, and steel. However, for prototypes, hardwood, industrial plasters, fiberboard, and synthetic foam are used. We selected wood as the prototype mold material.

Figure 27 A vertical CNC milling machine used to machine prototype molds in Phase I

Figure 27 is a vertical CNC milling machine that was used to machine two prototype wooden molds in Phase I. The process involved building CAD models of the molds, creating surfaces, and creating tool paths for the CNC machine. Since the size of the parts is fairly large and this machine is smaller, the parts were made in stages and it took about 16 hours of machining to produce the parts. The fabricated prototype molds are shown in Figs. 28 and 29.

Fi

Figure 28 Wooden mold of half the main trunk

Thermoforming Prototype Ductwork

SWA worked with Plastic Concepts & Innovations (PCI), a leading consulting company in the area of thermoforming. The first step was to select the type of thermoforming process. Since this was for fabricating the prototype, conventional vacuum forming was selected in order to keep the process simple. Since the selected ductwork cross-section was circular (it could just as easily be elliptical, or other geometrical shape), it had to be made in two halves and bonded together. There are several methods of bonding – thermal fusion, ultrasonic welding, and solvent bonding. In Phase I, solvent bonding was utilized to join the halves to form full sections. This could have been avoided if twin-sheet thermoforming were employed. Because it is complex and considered unnecessary to achieve Phase I objectives, it was not utilized.

Figure 31 Main trunk mold positioned on the thermoformer

A photograph of a single-sheet thermoformer is shown in Fig. 30. The process of forming involves heating the plastic sheet, placing it on the mold secured to the thermoformer platform, applying the vacuum, and cooling the part. This cycle is repeated and is virtually a continuous production process. The entire operation takes less than 4 minutes of cycle time.

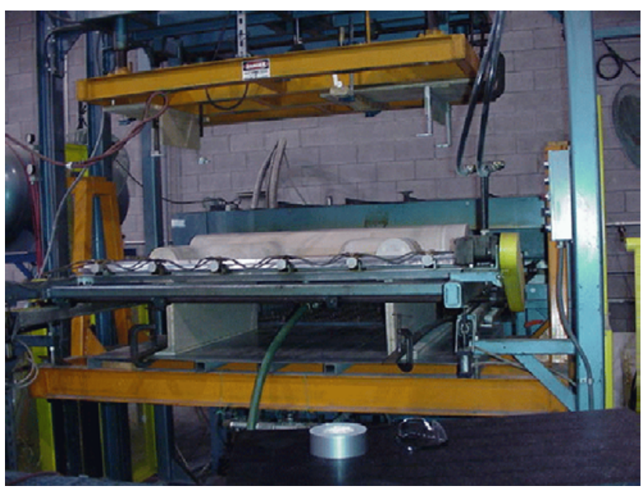


Figure 30 Single sheet thermoformer used to form the Phase I prototype duct components

Figures 31 and 32 show the molds of the main duct trunk and the branch, respectively. Plastic sheets of 65"x42" and 65"x22" were used to form the main trunk and the branch, respectively. The nominal thickness of the sheet was 0.125". Figures 33 and 34 are the pictures of the formed ductwork.

Figure 32 Branch mold placed on the thermoformer

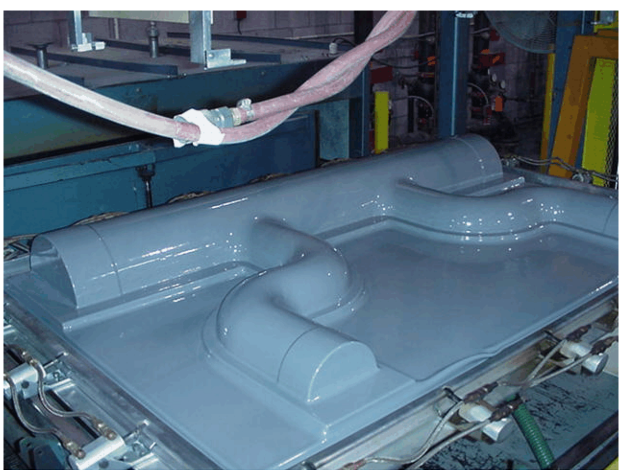


Figure 33 Formed main trunk half

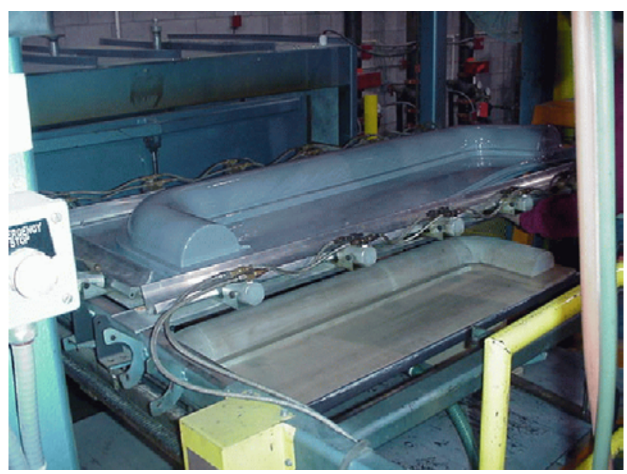


Figure 34 Formed branch half

The formed parts were machined to remove excess sheet material by a CNC machine, as illustrated in Fig. 35. Since these parts are symmetrical halves, they are bonded together using solvent bonding.

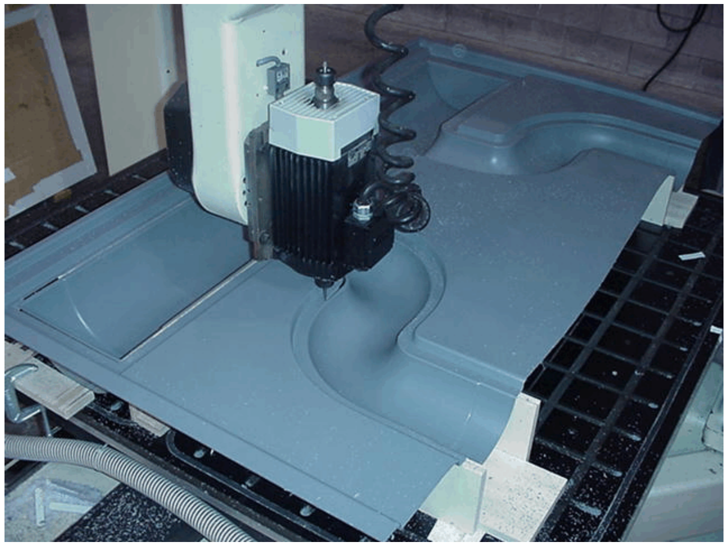


Figure 35 A CNC machining the excess sheet material from the trunk half. At production scales the trimmed excess is readily recycled.

Solvent bonding is achieved using PVC cement, consisting of PVC resin, a solvent, and an evaporation retardant. This process is simple and takes only a few minutes. The assembled main trunk and branch parts are shown below in Fig. 36.

Figure 36 Duct halves made whole parts by bonding

Prototype Assembly and Leakage Testing

The next task was to assemble the main trunks and branches to form a duct system and test it for leakage. There are different joining methods - adhesive bonding and double sided pressure sensitive adhesive tape. During this phase standard PVC adhesive was used to assemble the duct system. Figure 37 shows the unassembled duct components. Three main trunks (10" diameter) and five side branches (6" diameter) were put together. For each main trunk, the end was cut and inserted into the enlarged end of the other main trunk, which was coated inside with PVC adhesive. The two pieces were held together for about 30 seconds and left for curing. This was repeated until all three trunk sections were assembled. The trunk sections were assembled such that the branch-outs from the middle were horizontal, while the branch-outs for the other two were vertical.

Figure 37 Finished duct components ready to be assembled

The final assembly of the ductwork is shown in Figure 38. It should be noted that the entire duct system was produced with thermoforming in two molds. Even though the top branches did not need any support, small temporary braces were provided until testing was performed.

Figure 38 Assembled Phase I prototype duct system, all produced in two thermoforming molds. The system was virtually leakproof.

Next, air leakage measurement was performed using the Minneapolis Duct Blaster. It is a calibrated air flow measurement system used to test airtightness of forced air distribution systems. The Duct Blaster consists of a molded fiberglass fan with a variable speed motor. It can move 1500 cfm air at zero pressure drop and 1,350 cfm at 50 Pa of back pressure. It is equipped with a digital pressure gauge. The procedure involved connecting the Duct Blaster to the main trunk (see Fig. 39) and sealing all other openings in the duct system. Once sealing is done, the duct is pressurized to a specified pressure and duct pressure and fan pressure are measured. Fan pressure is the velocity pressure and gives a measure of air flow, or the total leakage at the measured duct pressure. A representative system average duct pressure when operating is 25 Pascals. The system shown was pressurized to 50 Pa and leakage was below the measurement accuracy of the Duct Blaster, indicating negligible duct leakage. It clearly shows that solvent bonding used to join the halves of the ducts and PVC adhesive to join the trunk to branches were highly effective. If twin-sheet thermoforming were used there would be no need for solvent bonding, making the thermoformed duct even more leak-resistant.

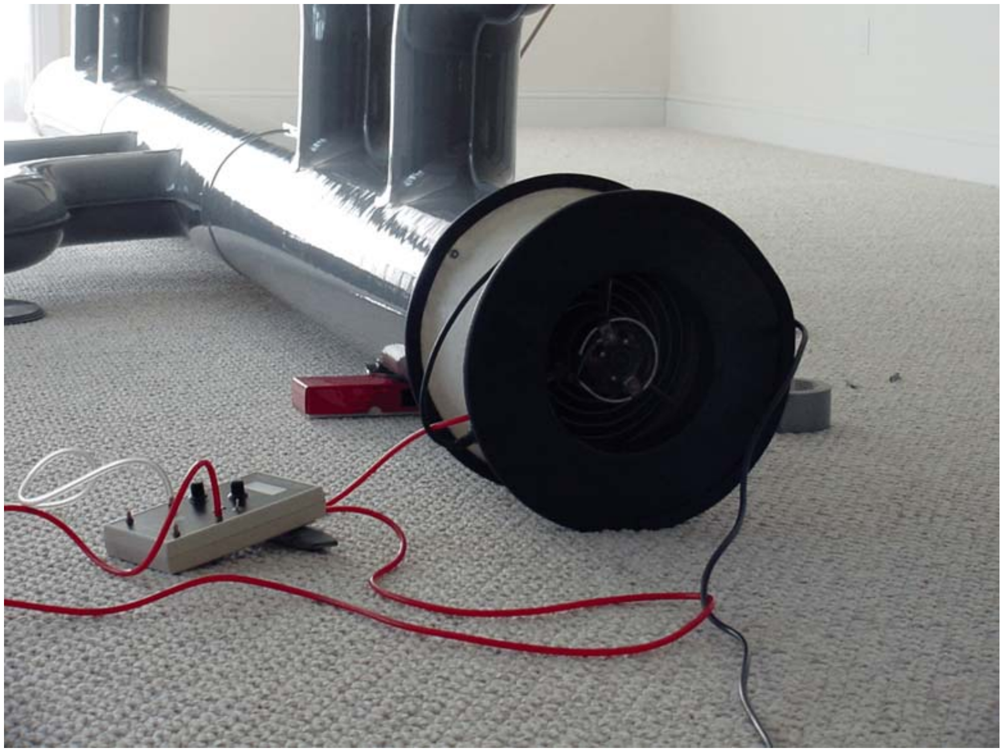


Figure 39 Duct Blaster hooked up to main trunk to measure air leakage

3.3 Assessment of Accomplishment of Phase I Objectives

The key goal of Phase I has been achieved: we have demonstrated the feasibility of thermoformed ductwork not only for recessed truss application, but for all conventional ductwork applications. This was achieved by researching candidate plastic materials and thermoforming technologies, studying various duct configurations, designing and building a full-size prototype duct system, and testing the same successfully.

Since the total success of this project is actually dependent on a well laid out Phase II research plan and a commercialization plan. The following sections describe Phase II research objectives and tasks.

4. PHASE II TECHNICAL OBJECTIVES

The following technical objectives are to be accomplished in the proposed Phase II research.

1. Determine optimum set of standardized duct components for system flexibility with a minimum number of molds.

2. Select the final candidate plastic material(s) for thermoformed ductwork.

3. Study the feasibility of single sheet forming, on-site thermoforming and twin-sheet forming.

4. Customize conventional thermoforming to include features of thermal fusion or automated solvent bonding at the factory; develop features for on-site thermoforming.

5. Study building codes and standards; develop strategies for code approvals.

6. Install and evaluate a prototype whole house duct system in recessed trusses.

5. PHASE II WORK PLAN & PERFORMANCE SCHEDULE

5.1 Develop Management Plan

This proposal represents an overview of Phase II development, written while Phase I work is still being completed. If Phase II funding is granted, the first priority will be to prepare a more detailed plan for research and product development.

What follows is an overview of the key tasks.

5.2 Determination of Optimized Duct Connections and Transitions

One of the attractive features of thermoformed plastic ducts is reduced friction losses. In addition to, no or low leakage, reduced friction loss (pressure drop) can reduce duct diameters (less material costs), and reduce fan power (hence reduced operating costs). During Phase I research, the issue of frictional losses was not considered. The Phase II effort will address the issue of friction losses in duct connections and transitions. In thermoformed duct systems, most of the connections can be integrated into the main duct. These connections or transitions can be very smooth. Also, extension runs from the main duct can include integral fittings requiring only one connection. In the case of conventional ducts, the duct fitting will have two connections.

In order to determine optimized duct connections, we will first review the ASHRAE Duct Fitting Database and identify potential duct fitting configurations. If we identify any potential configurations that are not listed in the database, we will explore employing computational fluid dynamics (CFD) analysis. SWA has significant experience in using CFD analysis for studying building air flow characteristics. Figures 40 and 41 illustrate prior examples.

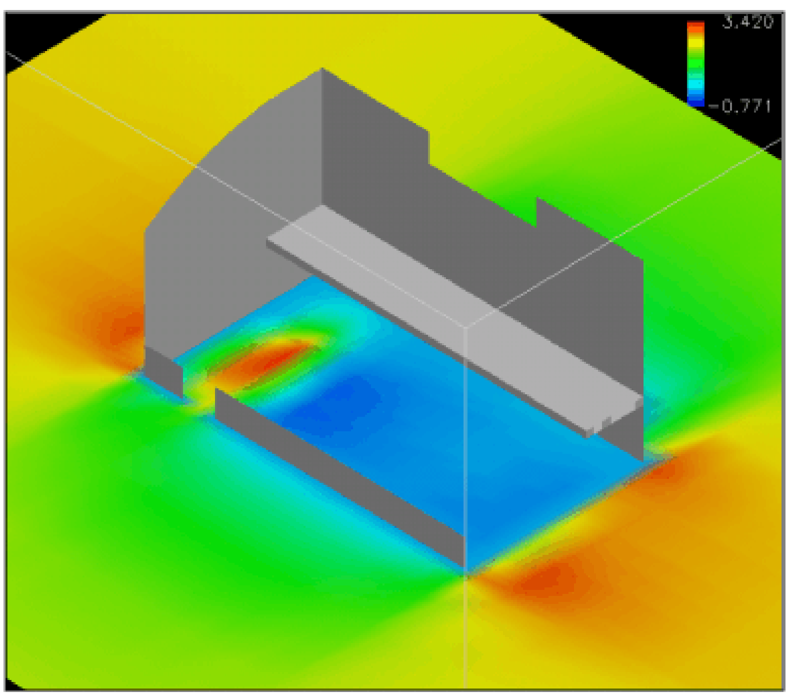


Figure 40 Horizontal velocity component distribution, CFD simulation of natural ventilation in the atrium of Oberlin College, Ohio.

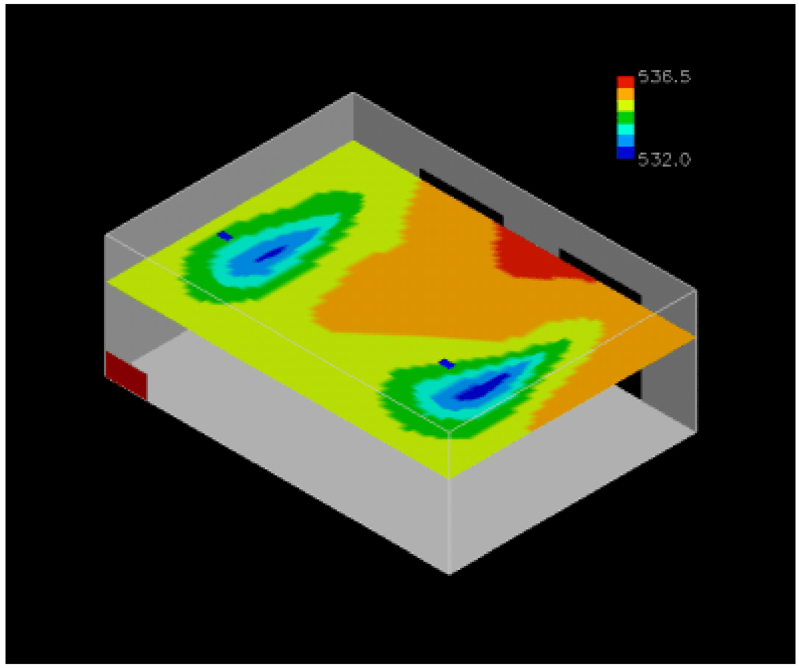


Figure 41 Air temperatures at 6 ft above floor with two supply registers, CFD simulation, room in a house in Phoenix, built by Del Webb Corp, part of SWA's research under DOE's Building America program.

During Phase I research, it was demonstrated that large parts measuring 5 ft long can be easily formed. There actually exist machines with a mold size of 20ft x 30ft. Also, as shown in Figs. 28 and 31, the main trunk mold was made in one piece to illustrate the feasibility of machining large molds.

During Phase II research, we will develop a process for the modular design of molds. The goal is develop a number of molds that will create any duct system configuration including the common main truck above or below the joists with branches running in the space between joists. Figure 42 illustrates that our prototype mold could be constructed as a combination of individual parts (A, B, and C). Parts A, B, and C can be rearranged to create many more duct layouts. This approach will be undertaken to cover an optimum number of duct connections and transitions. Duct diameters will be determined with additional research on friction losses.

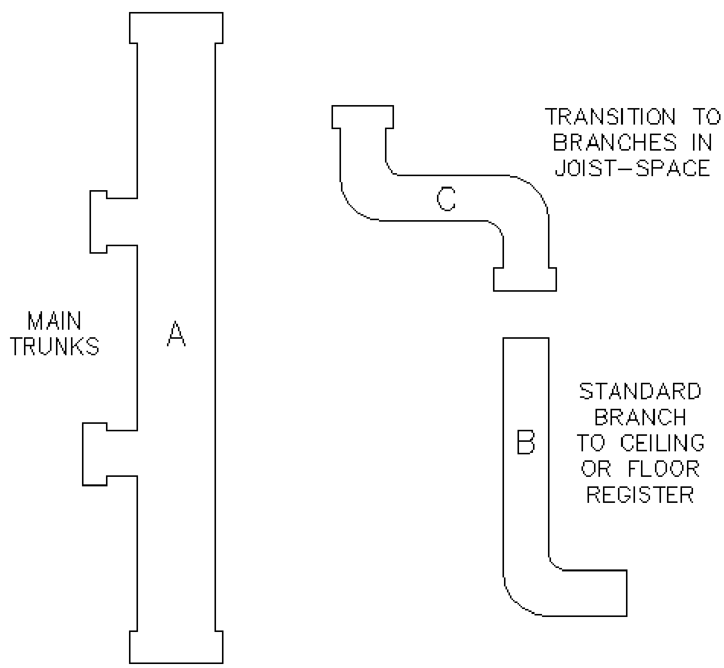


Figure 42 Modular mold design

5.3 Selection of the Final Candidate Plastic Material

During the Phase I effort, a PMMA/PVC blend was utilized for building the prototype duct system. However, it may not be our final candidate plastic material. It may be feasible to find a plastic material that meets the minimum required physical and operating characteristics, and has the lowest cost. We are proposing to develop material selection criteria with the help of PCI, as follows:

a) Identify a list of key property values that are desired for the final candidate material. Properties such as physical strength (this could be flexural strength, impact strength, or a combination of both), thermal conductivity, thermoformability, flammability rating, etc, will be considered.

b) For each property, normalize the value for each potential material with the desired value of the candidate material. For properties that do not have values assign a numerical ranking.

c) Assign a weighting factor for each property and rank the materials based on the final comprehensive figure of merit.

This multi-attribute analysis process will result in determination of the final candidate material.

5.4 Selection and Modification of Thermoforming Technology

Conventional thermoforming machines are designed to be stationary. They are designed to be sturdy and have a long life. Weight is a significant issue for a transportable on-site thermoforming machine. If the part to be formed is small in size, it is conceivable that a custom designed thermoformer that is transportable can be built. This is true for a single-sheet thermoformer. Complexity and size increase dramatically for a twin-sheet thermoformer. If our research shows that a customized single-sheet forming machine is adequate, we will take this approach. Otherwise, we will work on the development of twin-sheet forming.

First, we will study single-sheet thermoforming to include features of thermal fusion or automated solvent bonding at the factory; or we will develop features for on-site thermoforming. If this proves to be difficult, and it requires twin-sheet forming or any other variation, we will pursue that route. Determining factors would be equipment cost, transportation cost, ability to produce large parts, level of automation, and quality of product.

PCI will provide its expertise in this task. It will also identify candidate thermoforming manufacturers.

5.5 Building Codes and Standards

Under this task SWA will study the ASHRAE, ACCA, and SMACNA standards and guidelines for residential duct design and construction. SMACNA's Thermoplastic Duct (PVC) Construction Manual is extremely useful for developing minimum standards for fabrication and installation of plastic ducts. It provides a source of reference data for design engineers. The manual presents chapters on the material selection, standards of construction, and guide specifications. Even though this standard covers products that are extruded or injection molded plastic parts, it offers excellent guidance for thermoformed plastic ductwork. We will use this duct manual to the extent possible.

Eventually, SWA will work on enhancing this manual to include thermoformed plastic ductwork. SWA will obtain the necessary permits to install a prototype thermoformed ductwork system in a home. Most of the commercial thermoplastics already have UL listings. However, if it warrants, we will apply for UL certification.

5.6 Design and Field Evaluation of a Full-Scale Truss-Integrated Thermoformed Duct System

SWA will identify a prospective builder, such as Mercedes Homes with whom SWA has worked with extensively in Building America program efforts, to participate in the field evaluation of a prototype truss-integrated thermoformed duct system. The intent will be to construct two homes of the same plan and orientation, one with a conventional flex duct system in the attic (control house) and the other with the prototype system (prototype house).

SWA will design the HVAC system, including equipment sizing and duct design, for the prototype house using ACCA Manual J and D procedures, the industry standard. Calculations will be done assuming no duct gains or losses and no duct air leakage. The design of the HVAC system in the control house will be the responsibility of the builder and HVAC subcontractor.

The side-by-side comparison will allow for the evaluation and quantification of many important benefits by comparing:

- Installation costs including labor hours and material expenses
- Duct system air leakage via duct blaster testing
- Whole house tightness via blower door testing
- Air flow distribution via Low-Flo Balometer measurements of register air flows
- Duct heat gain via register supply temperatures and air flows
- Comfort via temperature and humidity measurements at several locations within each home
- Hourly energy use (compressor, fan, and total)

This type of side-by-side testing has proven to be a successful and convincing approach for several SWA Building America builder partners.

5.7 Independent Laboratory Testing of Prototype Ductwork

During Phase I, SWA conducted the duct leakage test. However, for Phase II research, SWA will work with NREL for laboratory and on-site performance testing. Performance testing may include duct leakage tests, pressure drop measurements, and testing for ability to withstand normal operating temperatures. SWA will work with NREL in developing test protocols, both laboratory and on-site.

5.8 Tasks Related to Business Development

While the primary focus of Phase II is technical (with technical items detailed in this chapter), there are several business-development issues that must be answered during Phase II to enable a successful transition to Phase III (commercialization).

1. Secure protection of intellectual property (patents & trademarks)

Securing patent and trademark protection as appropriate can greatly improve the chances of gaining outside investment, if required, during Phase III, and will make discussions with potential partners easier.

SWA has identified several concepts developed prior to and during Phase I that appear worthy of patent protection. Due to the time delays inherent in the granting of patents, the development of patent applications will be a high priority during the early part of Phase II.

2. Identification of target markets for product introduction

Successful product introduction will require identification of target, niche markets where the unique capabilities of the product are worth the cost. One important task during Phase II will be to explore these markets, determine whether they are in fact a good match to the technology being developed, and determine how much these markets are willing to pay for the product. Production builders and custom high-end builders could be the first targets.

3. Identification of and securing relationships with key partners

Once patent and trademark protection has been obtained and key technology demonstration experiments have been performed, discussions can be entered into with key partners. The range of potential partners under consideration includes:

- Thermoformers
- Plastics manufacturers
- Production builders
- Truss manufacturers
- National HVAC contractors

Ultimately, one path for commercialization may well be to license the technologies developed into a joint venture with one of these firms.

4. Develop technical materials needed for Phase III business plan

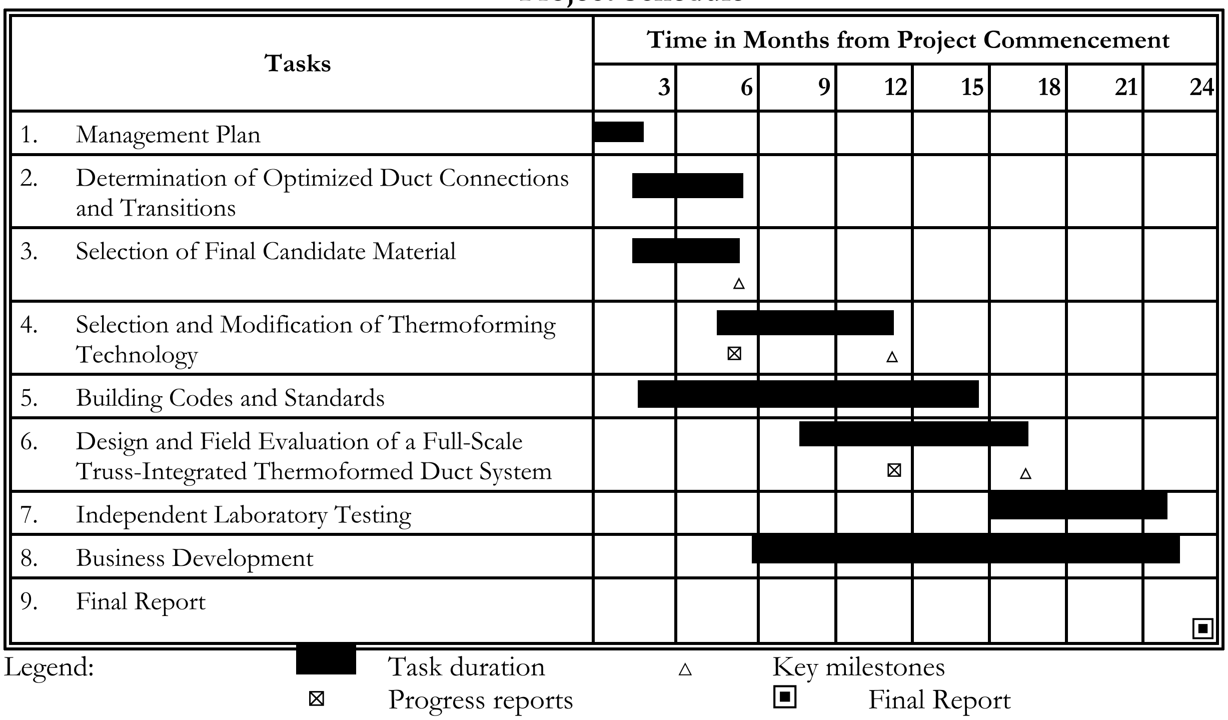
The final step during Phase II is to summarize what has been learned to enable the developing of a Phase III business plan.

5.9 Tasks Related to Contract Reporting

SWA will document the execution of the Phase II effort in a final report. The report will summarize the successes and shortcomings of the work.

The foregoing tasks are depicted graphically in the table below, which includes key milestones, semi-annual progress reports and a final report.

Project Schedule



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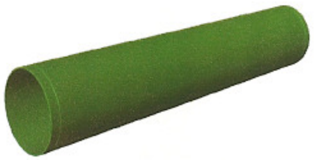

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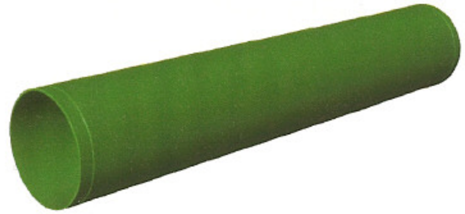

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