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Sound-Proof, Fire Resistant, Leak-Free and Super-Insulated HVAC Ducts

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Mechanical, Aerospace and Biomedical Engineering (MABE)

Sound-Proof, Fire Resistant, Leak-Free and Super-Insulated HVAC Ducts

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Sound-Proof, Fire Resistant, Leak-Free and Super-Insulated HVAC Ducts

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EXECUTIVE SUMMARY

The objective of this project was to design a more efficient duct system for residential heating, ventilation, and air-conditioning (HVAC) units. In particular, it was desired that the duct system capture the energy savings associated with placing the duct in the conditioned space, while still allowing the duct to be placed in the attic.

In order to accomplish this goal, multiple Visual Basic computer programs were developed to simulate the R-value associated with various insulation materials used to insulate the duct system. The insulation materials simulated included gases, solid insulating materials, and vacuum insulation. Based on the results of these simulations, it was decided to design a double-walled, vacuum-jacketed duct system.

After deliberating over a multitude of materials such as flex duct and PEX tubing, it was decided that the best material to use for this duct system design was PVC piping. The main reason PVC was selected is that it only requires PVC cement and epoxy to make the fittings air-tight. Other materials would require specialty flanges and O-rings.

One of the main questions associated with this design was whether or not it would have the ability to hold vacuum to the desired level over a long period of time. From modeling the duct system, it was found that the pressure needed to be maintained at 0.1 Pa or below in order to achieve a high R-value. Although this level was not achieved during the testing of the prototype, the results were still promising. During the testing, the lowest pressure level achieved was 25 Pa. However, a better vacuum pump is all that was needed to resolve this issue. The PVC also exhibited outgassing that caused the pressure to rise over a very short period of time; however, there is a patented device that could be used to resolve this issue. After the initial outgassing, the PVC managed to maintain the pressure relatively constant over a period of days.

Additionally, BeOpt was used to determine the annual energy cost in dollars for two homes: one located in Austin, Texas, the other in Minneapolis, Minnesota. There were three cases run for each of the homes. The first case assumed the home was built to the 2006 IECC standards. This served as the baseline. The second case assumed the same home was built to the 2015 IECC standards. This showed the amount of savings that could be expected just due to improvements in the codes. The final case assumed the same house was built to the 2015 IECC standards but also included the new duct design. In Austin, Texas, the new design yielded an extra 52% of cost savings per year as compared to the baseline savings associated with increases in code requirements from 2006 to 2015. As for Minneapolis, the savings were much more significant when using the new duct. The new design caused a 420% increase in the savings compared to baseline. This is potentially due to the additional supplemental heating shift observed in the simulation that was not present in the hotter climate zone.

However, the savings, while relitively large, show that this design would not be possible at the current time due to the high cost of PVC and the initial costs required to alter the current duct designs already set in place. The speculated payback time for the system is around 48 years, which is much higher than the lifespan of the system and thus unreasonable. Potential changes or technological advancements may decrease the cost significantly which would then make the design financially viable.

1. INTRODUCTION & OBJECTIVES

1.1 PROBLEM STATEMENT

The objective of this project was to design a sound-proof, fire resistant, leak-free, super-insulated HVAC duct. The foundation of this project was in the data collected by Dr. Miller that quantified the amount of energy being lost each year due to the ducts being placed in the attic. The program AtticSim was used for this modeling process. An example of the data generated by AtticSim for a home in Austin, Texas is shown in Figure 1.

There are two primary modes of energy loss from a duct system. The first is the heat transfer that occurs due to the temperature gradient between the conditioned air flowing through the duct and the air outside of the duct. The second method of energy loss from a duct system is air leakage. If the duct is not placed in the conditioned space, then any air that leaks out of the duct system is lost to the environment.

One method of reducing the energy lost in the attic space is to increase the amount of insulation placed in the attic. This extra insulation serves to increase the resistance to heat transfer between the attic and the conditioned space through the attic floor. In the HVAC industry, and the field of Heat Transfer in general, the resistance to heat transfer is described by the associated R-value of the material. An effective R-value can also be calculated for a system of materials. The higher the R-value, the larger the resistance to heat transfer. Therefore, increasing the amount of insulation in the attic increases the R-value associated with the attic. The attic floor R-value is plotted along the abscissas of Figure 1. Increasing the R-value of the attic floor yields large energy savings up until a value of roughly R-15 is achieved. Anything beyond this starts to exhibit diminishing returns.

Figure 1 shows that further energy savings can be realized by sealing the attic floor, increasing the insulation on the ducts, and reducing the air leakage associated with the duct system. By increasing the amount of insulation placed on the duct system, it decreases the amount of heat transfer that will occur through the wall of the duct. This results in the air arriving at the conditioned space closer to the temperature required to condition the space. Therefore, less air would have to be conditioned to get the conditioned space to the desired temperature. However, even after these improvements are made to the degree represented by the orange bar in Figure 1, there is still a significant amount of energy being consumed by having the ducts in the attic.

As can be seen by the green bar in Figure 1, removing the ducts from the attic results in an order of magnitude reduction in energy consumption when compared to the insulated ducts represented by the orange bar. The main factor behind these large energy savings is that by placing the ducts in the conditioned space, all the energy lost by the duct system is still being gained by the conditioned space. When the ducts are placed in the attic, the cooled or heated air is lost to the environment – not the conditioned space.

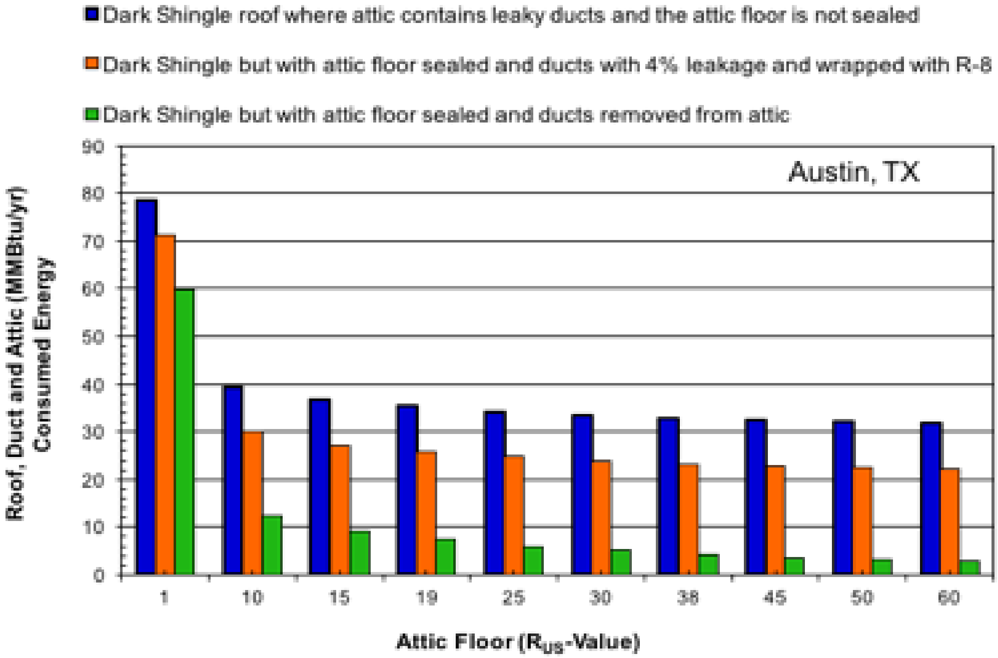


Figure 1. Initial calculations of energy loss due to the ductwork being in the attic

The obvious question is: If there are so many benefits from placing the ductwork in the conditioned space, then why is it still standard practice to place the ducts in the attic? This is a multi-faceted issue with no single right answer. There are influencing factors on both sides of the equation: the people buying the homes and the builders and contractors building the homes. In some cases, it is as simple of a reason as not wanting to sacrifice valuable living space in order to remove the ducts from the attic. In other cases, there can be a multitude of conflicting requirements, such as aesthetic considerations, architectural design limitations, etc. that cause it to be much more complicated. Those are just some simple examples used to give some idea to the reader of the many different complex factors that are associated with placing the ducts in the conditioned space. The key takeaway is that for a typical U.S. home, the current reality of the housing market is that the ducts will be placed in the attic.

1.2 OBJECTIVES

The primary objective of this project was to design an HVAC supply duct that had zero losses associated with heat transfer or air leakage. To help accomplish this primary objective, the secondary objective was to create computer programs that would: 1) aid in the design of the duct system by allowing different insulation materials and configurations to be compared and 2) use static regain techniques to size the ducts in a model house.

1.3 PRESENT DESIGNS

The typical residential HVAC system in the United States consists of an outdoor unit (condenser), an indoor unit (air handler), and a duct system. The condenser and the air handler are the units that contain all the equipment necessary for the addition or removal of heat from the conditioned space. Both systems are important aspects to improving the overall efficiency of an HVAC system; however, these units were not the focus of this design. Instead, only the delivery of the conditioned air through the ductwork of the system was considered.

Before expanding further on this topic, some definitions of the terminology associated with ducts are needed. The main duct that spans from the air handler to the end of the house is often referred to as the “trunk”. Although the trunk can change diameter multiple times along its path, it will typically always be the largest duct in the system. Other ducts break away from the trunk and are routed to each of the vents in the house. These ducts are referred to as “branches.”

In a typical residential HVAC system, all the ductwork is placed in the, often unconditioned, attic of the home. The current International Energy Conservation Code (IECC) requires that the ducts be wrapped in R-8 insulation in an effort to reduce heat loss from the duct. [1]

During installation, the duct system is often constructed on site. The installation process involves the installer cutting a hole into the side of the trunk and then connecting the branch to the newly formed hole. The connection between the two is then wrapped with tape. Because the cut is made on site and not prefabricated, the fit between the trunk and the branch will not always be ideal. This non-ideal connection results in leaking air, which leads to higher rates of energy loss.

2. PRELIMINARY DESIGN AND MODELING

2.1 PRELIMINARY DESIGN

The initial design approach for this project was to incorporate a double-containment duct system with insulation placed in the annular region. During the research stage, it was found that this type of insulation technique is already used in both the cryogenic field as well as for Dewar flasks. In both of these applications, the insulation R-values are highly important to prevent the large heat transfer rates that would typically be associated with large temperature gradients. For these applications, one common insulating material that is used is to pull vacuum in the annular region between the two layers. Based on this information, one of the main aspects of the design was to find a way to scale the double-containment system up to a size that is useable for insulating the ducts in a residential home.

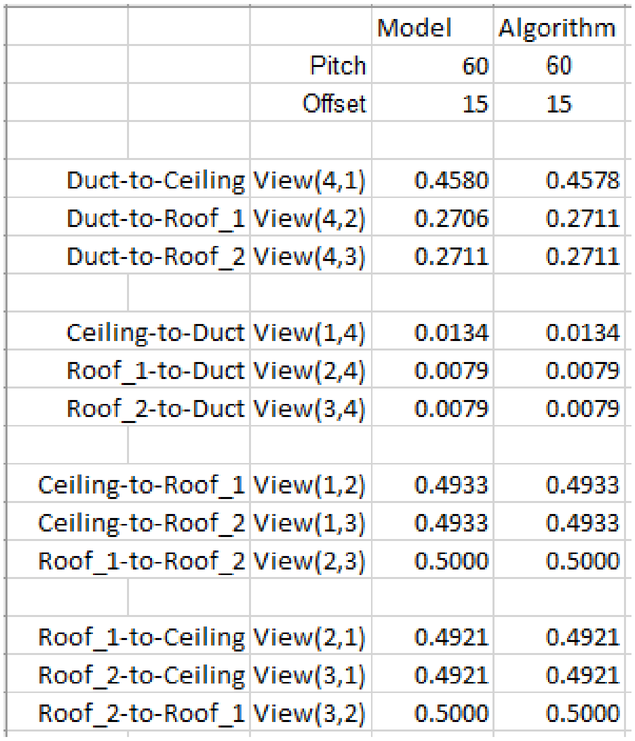
2.2 R-VALUE MODELING

One of the first major aspects of this project was to develop a computer program using Visual Basic in Microsoft Excel that could be used to quickly simulate the performance of various duct designs. The purpose of this program was to calculate the associated R-value of the duct system as various parameters such as attic geometry, insulation material used, and size of the annular gap were changed. The outputs of this computer program were used to determine which design configuration would be used for the final design and prototype.

One major component of this program was coding in the ability to calculate the radiation heat transfer occurring to the duct regardless of the placement of the duct in the attic. There is not sufficient room in this paper to cover all of the aspects of radiation heat transfer. If needed, Incropera, DeWitt, Bergman, and Lavine cover this topic extensively in *Fundamentals of Heat and Mass Transfer.* [2] This textbook was an invaluable resource during the development of the computer program.

Because this simulation tool was serving as the foundation from which the rest of the design choices were made, it was crucial to prove the accuracy of the simulation. For the radiation heat transfer aspect, Hottel’s crossed string method was used to verify the outputs of the algorithm. [3] In using this method, it was assumed that the duct system in the attic was long enough to be modeled as having infinite length. The view factors calculated in Table I are intermediary values used to calculate the radiation heat transfer rates. Table I shows the results calculated by hand for a test model as compared to the results of the algorithm. As can be seen, the results of the algorithm, closely matched the results found from the model.

Table I. Comparison between the predictions made by the computer algorithm and the hand calculations for a test model



		Model	Algorithm
	Pitch	60	60
	Offset	15	15
Duct-to-Ceiling	View(4,1)	0.4580	0.4578
Duct-to-Roof_1	View(4,2)	0.2706	0.2711
Duct-to-Roof_2	View(4,3)	0.2711	0.2711
Ceiling-to-Duct	View(1,4)	0.0134	0.0134
Roof_1-to-Duct	View(2,4)	0.0079	0.0079
Roof_2-to-Duct	View(3,4)	0.0079	0.0079
Ceiling-to-Roof_1	View(1,2)	0.4933	0.4933
Ceiling-to-Roof_2	View(1,3)	0.4933	0.4933
Roof_1-to-Roof_2	View(2,3)	0.5000	0.5000
Roof_1-to-Ceiling	View(2,1)	0.4921	0.4921
Roof_2-to-Ceiling	View(3,1)	0.4921	0.4921
Roof_2-to-Roof_1	View(3,2)	0.5000	0.5000

In this section, the Guard means the outer duct. Figure 2 show the results of the simulation for a variety of different insulation materials placed in the annular gap between the Guard and the inner duct. The insulation materials tested include both gases and solid insulation materials. The results of this section can be divided into three parts. In the first part, both the Guard and air duct have low emissivity surfaces. This case would require the use of a special kind of paint or foil on both the inside surface of the Guard and the outer surface of the inner duct. The results for the first part can be seen in Figure 2.

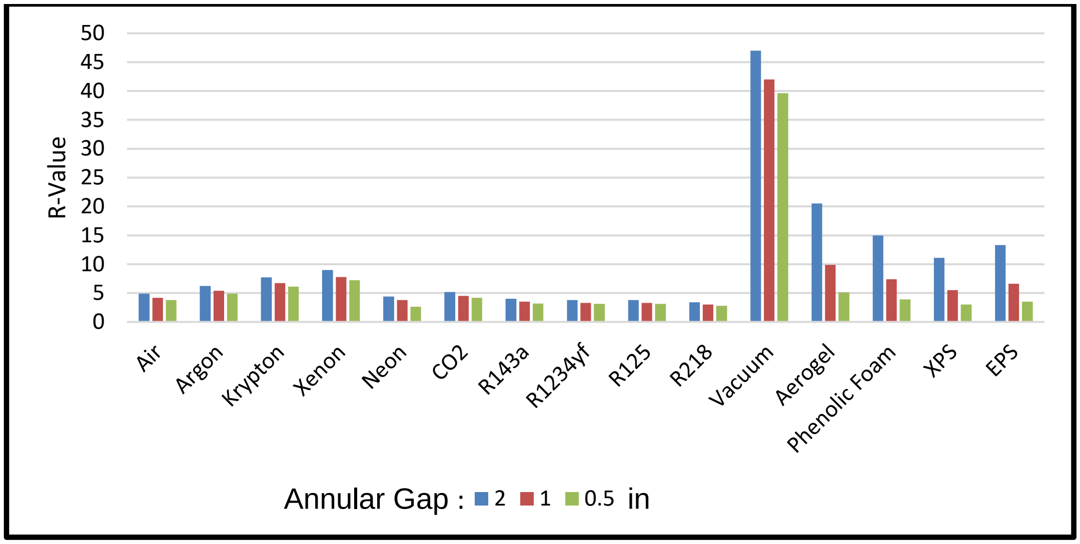


Figure 2. R-value for different types of materials where both ducts have emissivity of 0.05

From Figure 2, it is easy to tell that using vacuum insulation in the annular gap between the ducts provided the largest R-value by a significant margin. From this scenario, even with only a 0.5 in. annular gap, the system achieves roughly R-40. This is a significant improvement over the R-8 insulation currently used. For an annular gap thickness of two inches, Aerogel is another material that performed significantly above the current standard insulation value. Aerogel is a product developed by NASA. Aerogel is a solid insulation material so it would be much easier to use than vacuum insulation; however, due to its high cost per foot, the idea was discarded.

During the second iteration of modeling, it was assumed that both the Guard and inner duct had an emissivity of 0.9. Because the material of the duct had not yet been chosen, this value of emissivity was used as a rough estimate of the typical emissivity of a non-polished solid material. By using this value of emissivity, the simulation returned an estimate of the R-values corresponding to using ducts straight from the manufacturer. The results can be seen in Figure 3.

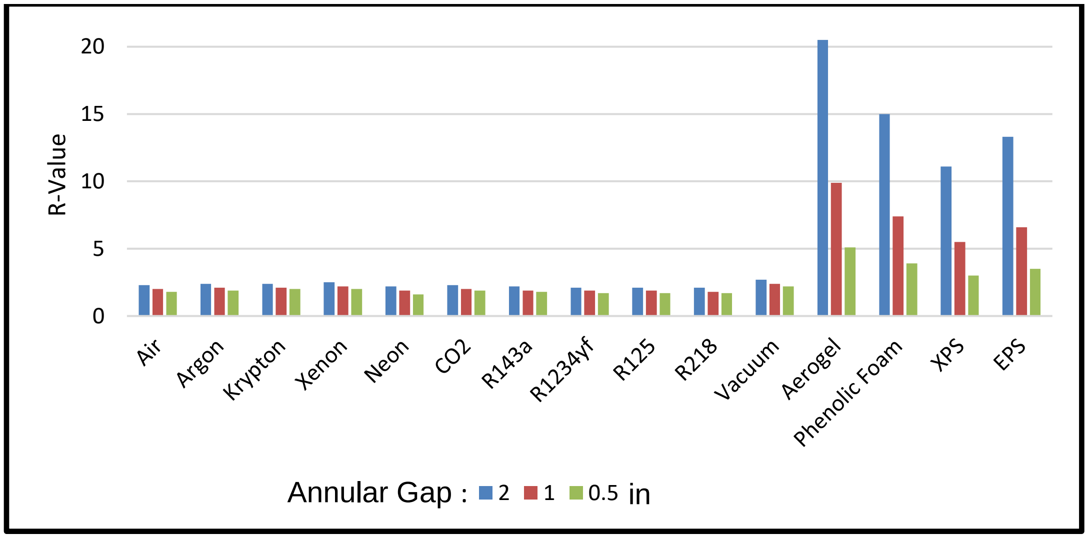


Figure 3. R-value for different types of materials where both ducts have emissivity of 0.90

When Figures 2 and 3 are compared, it is obvious that it is necessary to have low emissivity surfaces if vacuum insulation is used. This result was expected because radiation heat transfer will be the dominant mode of heat transfer across the vacuum space because there is not enough air present for conduction or convection to occur to any appreciable degree. From Figure 3, where neither surface is low emissivity, the R-value associated with the vacuum insulation is no better than just placing air in the annular gap. However, it would be difficult to apply a paint or foil to the inside diameter of the Guard in order to give it a low emissivity surface. This made it desirable to analyze the system performance if only one surface had low emissivity. The third iteration of modeling assumed that only the outside surface of the inner duct was low emissivity. The results are shown in Table II.

Table II. R-value for the Vacuum where HVAC duct has emissivity of 0.05

Annular Gap (in)	**2**	**1**	**0.5**
Vacuum (R-Value)	31.1	25.6	22.9

As can be seen in Table II, it is possible to reach up to R-31 with an annular gap of two inches. Even the R-23 provided by the 0.5 in. annular gap is a significant improvement over the current standard, so it was decided that only one low emissivity surface was required in the design. Recall, conventional ducts are only required to be insulated to R-8 to meet the IECC 2015 code. [1]

From the preliminary results of the models, it appeared that pulling vacuum in the annular gap was a very promising design approach. However, there was another issue associated with vacuum insulation that needed to be modeled. During the above simulations, it was assumed the vacuum in the annular gap had a pressure of 0.01 Pa. Due to various factors that will cause the level of vacuum to fluctuate over time, it was necessary to investigate what level of pressure was needed to achieve the desired R-value. Figure 4 shows the R-value as a function of the pressure in the annular gap. This plot was based on a model that had a low emissivity surface only on the outer diameter of the inner duct and a one inch annular gap.

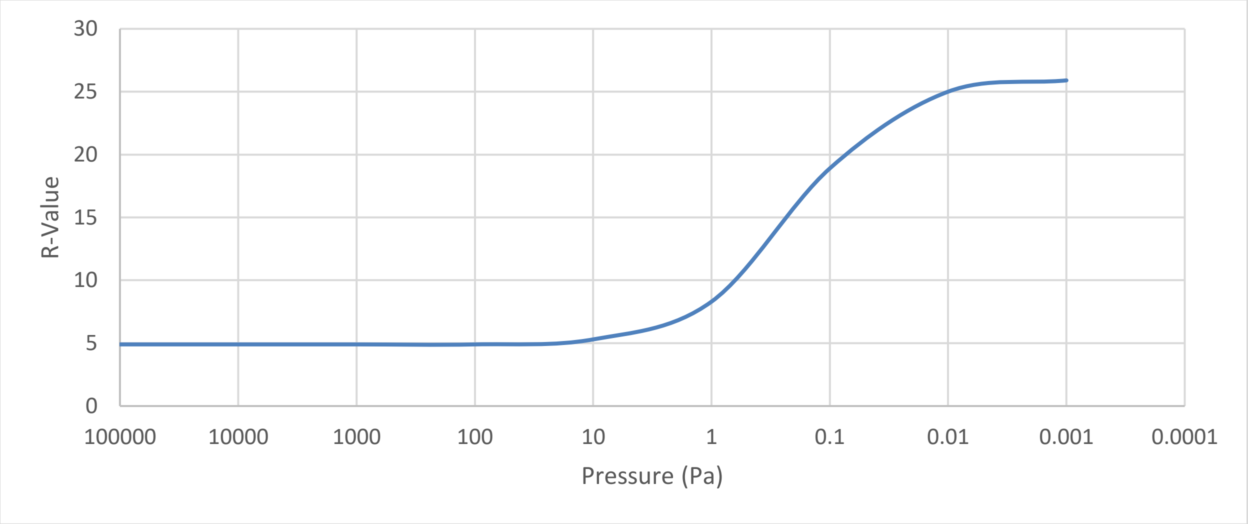


Figure 4. R-value as a function of the pressure in the annular gap

From Figure 4, it was apparent that the pressure in the annular gap had to be reduced to at least 0.1 Pa to achieve R-19. Anything above this level sees a rapid decrease in R-value. This matched expectations since the pressure in the annular gap is related to the amount of air in the gap. If there is too much air in the annular gap, then the other two modes of heat transfer will play a significant role.

3. DESIGN

3.1 CHOSEN INSULATION

After analyzing the results of the various models, it was decided that, out of all of the various materials that were tested, using vacuum to insulate the duct system was the most promising. This design was chosen for multiple reasons. One of the main factors was that using vacuum insulation in the models provided consistently high R-values that were at least three times higher than current building code requirements. Another major factor was the cost. Aerogel was the only other material used in the simulations that managed to provide an R-value comparable to that of the vacuum insulation. However, the current cost of Aerogel makes it not feasible for use in the design of a duct system for residential homes.

3.2 DESIGN RESTRICTIONS

For this design, there were numerous restrictions and criteria that had to be met. In some cases, these restrictions were externally applied in the form of cost or code requirements while in other cases, the restrictions were due to engineering principles that had to be satisfied in order for the design to work.

One of the external restrictions placed upon the design were the building code requirements associated with residential homes. In particular, it is required that a duct that runs through a plenum space must be made from a material that meets the 25/50 flame spread and smoke developed tests. The requirements for these tests are laid out by ASTM International in ASTM E84 [4]. This code limits the types of material that can be used to construct a duct system to those materials that pass the 25/50 regulation. This greatly limited the materials that could be used in the design.

Another factor that limited the type of material that could be chosen were the physical limitations of the material. Pulling vacuum in the annular region induces a large pressure difference between the annular gap region and the atmospheric air in the attic. This difference in gas pressure will result in the Guard of the duct essentially being subjected to a compressive force. Therefore, the chosen material had to be able to withstand this load.

The cost of the duct system was another external restriction placed on the design. In particular, the payback period of the system needed to be quick enough to give consumers a reason to switch to the new design. This further restricted the type of material that could be used for the duct system.

Another restriction placed upon the design is that it had to be able to hold vacuum for extended periods of time. One aspect of this was that the design had to have a way to seal off the annular region to prevent any leakage at the diffusers or fittings used in the duct system. Along with this, the material used to construct the duct had to exhibit very low levels of outgassing.

3.3 CHOSEN DUCT MATERIAL

After deliberating over a multitude of materials such as flex duct and PEX tubing, it was decided that the best material to use for this duct system design was PVC piping. PVC was selected for multiple reasons. The first reason is that PVC is already in widespread use, and it is already possible to buy all of the necessary fittings needed to construct a duct system. Another reason PVC was selected is that it is relatively easy to work with. This means that construction companies would not need to have specialized training for their workers in order to implement this design. Another advantage PVC offered over the other materials is that the connections (tees, wyes, etc.) can be made completely air-tight by just using PVC cement and epoxy. Other materials would require a specialized flange and O-ring combination in order to create an air-tight seal.

4. RESULTS AND DISCUSSION

4.1 PROTOTYPE

The first prototype that was constructed is shown below in Figure 5. The system was constructed using a 2 ½ inch inner diameter pipe and a 6 inch outer diameter pipe. The system was sealed with silicone flanges at the ends, and the fittings were glued together with PVC cement. Between the silicone flanges, rubber gaskets were used to seal the connection. As shown, a Schrader valve is inserted into one of the end flanges and is used for connection to the vacuum pump located in the upper right corner of Figure 5. When vacuum was pulled on the apparatus, it was discovered that the PVC cement did not produce an air-tight seal. It is theorized that the application of the cement was not thorough enough, and ensuing prototypes were more carefully constructed. In order to improve the air-tightness of the seals, an epoxy was also used. This yielded much better results.

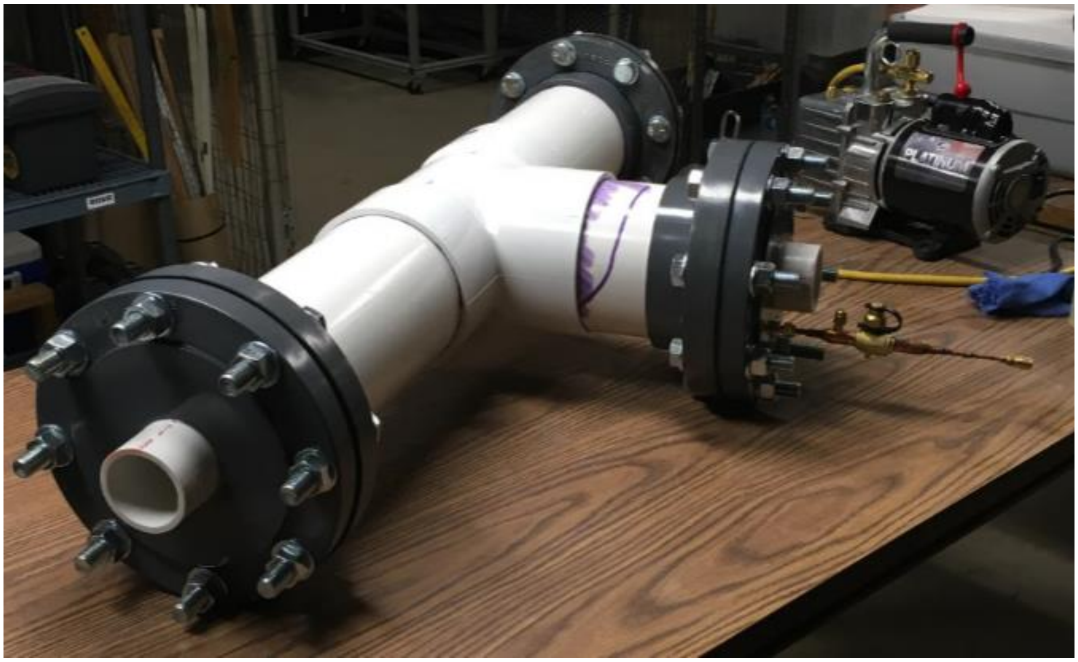


Figure 5. The first prototype of the design

4.2 TESTING

One of the main questions associated with this design was whether or not it would have the ability to hold vacuum to the desired level over a long period of time. In order to test this, a vacuum pump was used to pull vacuum on the prototype. Once this was done, the vacuum was removed and daily measurements of the pressure inside of the prototype were taken. The results of these tests can be seen in Figure 6.

Before testing the prototype, a preliminary pressure rise test was performed. For this test, the apparatus consisted of a short section of PVC with two endcaps used to seal the ends. As can be seen in Figure 6, the pressure rise was rather drastic during this test. This test revealed the importance of sealing the connection used to insert the Schrader valve.

Figure 6 also shows the results of two outgassing tests performed on the prototype. As can be seen, the lowest pressure level achieved was 25 Pa. During the first test, the pressure was reduced to 33 Pa before removing the vacuum pump. After 72 hours, the pressure had increased to 104 Pa. During the second test, the pressure was initially reduced to 25 Pa. After 42 hours, it had increased to 114 Pa. As can be seen, in both cases the pressure rose significantly during the first few hours after the vacuum pump was removed and then leveled off and remained relatively constant for the rest of the test. This initial spike was due to outgassing that was occurring from the PVC ducts.

Although the pressure in both of the tests was still significantly higher than the 0.1 Pa level needed for the desired R-value, the results of the test were still promising. In both cases, after the initial outgassing, the prototype managed to maintain the pressure at a relatively constant level over the course of days. Due to time constraints, the outgassing tests could not be run for longer than they were. Future testing will be required to see if the design can maintain the vacuum level over the course of months and years.

While doing research into the outgassing of PVC a promising solution to the problem was found. There is currently a patent for a method that eliminates the outgassing that occurs with PVC. [5] This patent allows PVC to be used in high- and ultra-high vacuum applications. This means that PVC would be usable for this design. Unfortunately, due to time constraints the patented design could not be tested on a new prototype. However, it does provide a promising outlook for the future testing of this design.

Another problem that arose during these tests was that vacuum was not reduced to a low enough pressure level. This problem could be solved by using a better vacuum pump.

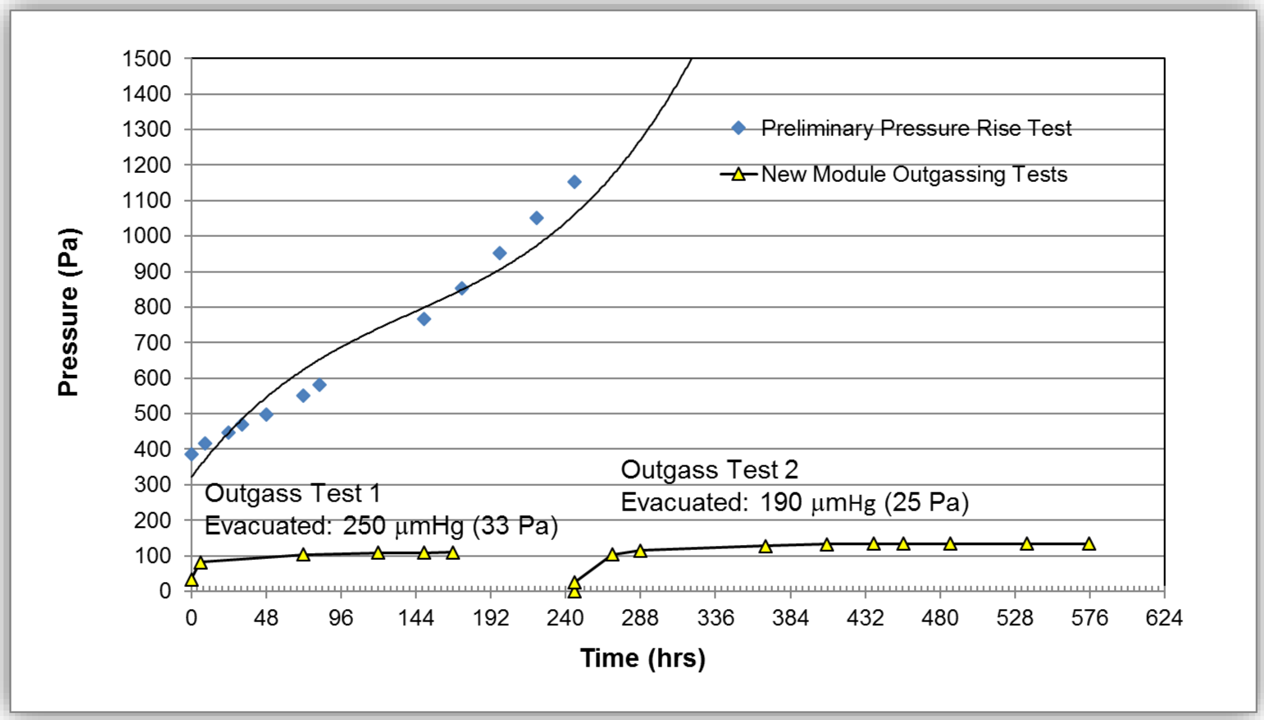


Figure 6. The pressure inside of the prototype with respect to time

4.3 STRUCTURAL INTEGRITY

One of the main challenges associated with a duct design utilizing vacuum insulation is the structural integrity of the system. The Plastics Pipe Institute (PPI) documents design classifications for PVC pipe. According to the institute, the design stress of PVC is dependent on the calcium carbonate in the PVC formula. However, it is found that most design stresses for PVC are between 1,000 and 2,000 psi. Using this information, the group wanted to analyze whether or not the PVC duct system could hold under vacuum. Assuming principals of a thin-walled pressure vessel, the largest stress the system will face is hoop stress. Table III below shows the resulting hoop stress at each diameter assuming a pressure of 14.7 psi. As seen, the larger the diameter, the larger the hoop stress. However, each calculated hoop stress is well within the proportionality limit specified by the PPI.

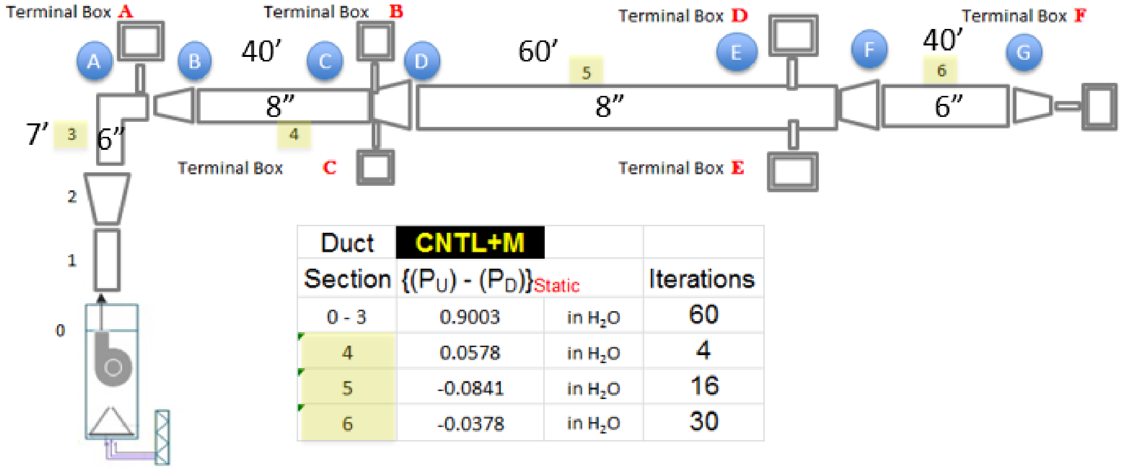
Table III. Hoop stress calculations assuming a pressure of 14.7 psi

Diameter (in)	Hoop Stress (psi)
4	117.60
6	141.12
8	188.16
10	196.00
12	235.20

4.4 COST ANALYSIS

Once the challenge of structural integrity had been addressed, the group turned toward designing a supply duct system. The task was to fit a duct system into a 2,000 square foot house. This 2,000 square foot house was used as a model for the cost comparison calculations. The house has a mechanical closet where the blower is located. The duct is run from the closet to the attic and then across the house. There are a total of 6 registers for this duct system, and a 3-ton unit is used. When designing the duct system, the group decided to use a high velocity duct system and used the technique of static regain. A high velocity duct system was chosen because it allows the diameters of the ducts to be much smaller than the ducts used with traditional systems. This was important for cost purposes since the cost per foot of PVC increases as the diameter of pipe increases.

Total pressure within a system is equal to the sum of velocity and static pressures. Static pressure is the pressure that causes the air in the duct to flow whereas velocity pressure results from the air movement. The goal of the static regain method is to have the same static pressure at each branch and terminal. By creating an Excel code, the group calculated a duct design that satisfies the static regain method. The supply duct system and excel results are shown below in Figure 7.

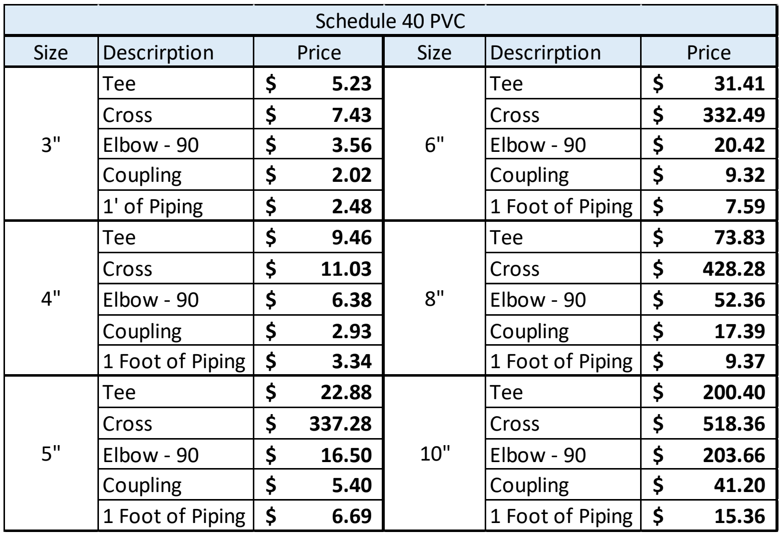


Duct Section	CNTL+M $\{(P_U) - (P_D)\}_{Static}$		Iterations
0 - 3	0.9003	in H_2O	60
4	0.0578	in H_2O	4
5	-0.0841	in H_2O	16
6	-0.0378	in H_2O	30

Figure 7. The duct system designed for the model home

Using the above system, the group then looked into the cost of building the duct. Table IV below shows the cost associated with certain fittings at respective diameters of PVC pipe. As shown, as diameter increases, the cost for each fitting also increases. At diameters of 5 inches and above, the prices begin to increase exponentially. For example, the cost difference between a 5-inch cross and a 4-inch cross is roughly $326. In fact, the high cost of crosses at large diameters forced the group to steer clear of that certain type of fitting. In place of a cross, it is much cheaper to just use two tees.

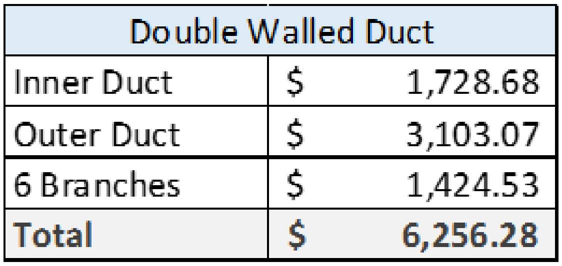
Table IV. PVC cost data



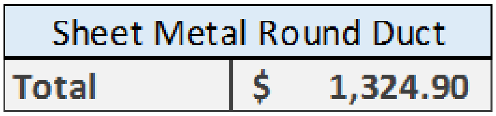
Schedule 40 PVC					
Size	Descrirption	Price	Size	Descrirption	Price
3"	Tee	$ 5.23	6"	Tee	$ 31.41
	Cross	$ 7.43		Cross	$ 332.49
	Elbow - 90	$ 3.56		Elbow - 90	$ 20.42
	Coupling	$ 2.02		Coupling	$ 9.32
	1' of Piping	$ 2.48		1 Foot of Piping	$ 7.59
4"	Tee	$ 9.46	8"	Tee	$ 73.83
	Cross	$ 11.03		Cross	$ 428.28
	Elbow - 90	$ 6.38		Elbow - 90	$ 52.36
	Coupling	$ 2.93		Coupling	$ 17.39
	1 Foot of Piping	$ 3.34		1 Foot of Piping	$ 9.37
5"	Tee	$ 22.88	10"	Tee	$ 200.40
	Cross	$ 337.28		Cross	$ 518.36
	Elbow - 90	$ 16.50		Elbow - 90	$ 203.66
	Coupling	$ 5.40		Coupling	$ 41.20
	1 Foot of Piping	$ 6.69		1 Foot of Piping	$ 15.36

Using the data above in Table IV, the cost of materials for a PVC double walled duct is compared to the cost of materials for a round sheet metal duct. The results are shown below in Table V. As seen, the cost to construct the system with PVC is roughly $4,900 more expensive than sheet metal. There are numerous reasons as to why the PVC duct is much more expensive. The main reason is that the vacuum system calls for essentially constructing two separate duct systems in order to create a vacuum in the annular gap.

Table V. Cost of materials analysis



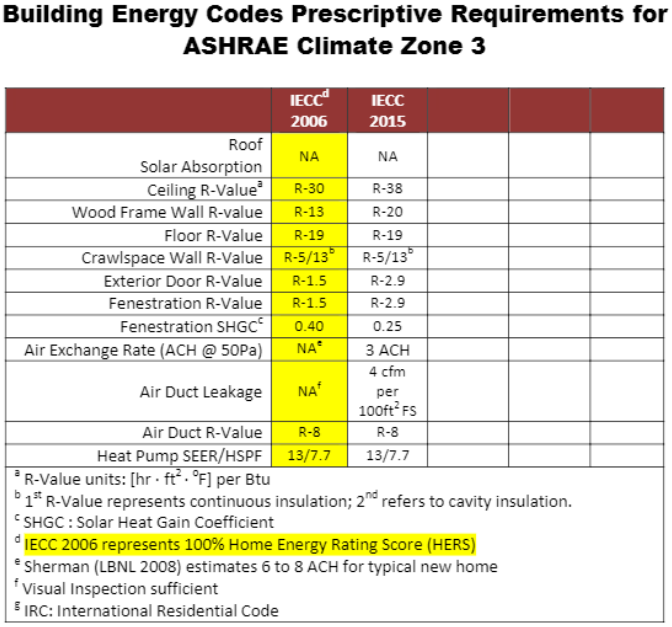
Double Walled Duct	
Inner Duct	$ 1,728.68
Outer Duct	$ 3,103.07
6 Branches	$ 1,424.53
Total	**$ 6,256.28**



Sheet Metal Round Duct	
Total	**$ 1,324.90**

4.5 ENERGY SAVINGS

In order to determine the energy savings of using a zero-emissions duct design, BeOpt was used to simulate the model house using three different setups. The first setup was created using the 2006 International Energy Conservation Code, and was used to determine a basis for energy savings. [6] The current code, determined to be the 2015 International Energy Conservation Code, was added to ascertain the current energy savings, making it easier to visualize potential savings. [7] For the final setting, the 2015 International Energy Conservation Code was used again, but the duct was moved to the conditioned space. [7] By moving the duct into the conditioned space in BeOpt, it simulates the energy usage of a no emissions duct that the new design would theoretically also yield. In all cases, the same appliance settings were added to better reflect the target homes. These additions were kept as simple as possible to accurately determine the Home Energy Rating System (HERS) score of the building. An example of the settings used to create the BeOpt simulation can be seen below in Figure 8. The values shown in Figure 8 differ for each of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) climate zones. It should be noted that BeOpt simulations were created for each of the ASHRAE defined American climate zones, but further analysis was only conducted on climate zones 2 and 6. [8]



Building Energy Codes Prescriptive Requirements for ASHRAE Climate Zone 3

	IECC[d] 2006	IECC 2015			
Roof Solar Absorption	NA	NA			
Ceiling R-Value[a]	R-30	R-38			
Wood Frame Wall R-value	R-13	R-20			
Floor R-Value	R-19	R-19			
Crawlspace Wall R-Value	R-5/13[b]	R-5/13[b]			
Exterior Door R-Value	R-1.5	R-2.9			
Fenestration R-Value	R-1.5	R-2.9			
Fenestration SHGC[c]	0.40	0.25			
Air Exchange Rate (ACH @ 50Pa)	NA[e]	3 ACH			
Air Duct Leakage	NA[f]	4 cfm per 100ft^2 FS			
Air Duct R-Value	R-8	R-8			
Heat Pump SEER/HSPF	13/7.7	13/7.7			

[a] R-Value units: [hr · ft^2 · ^{o}F] per Btu

[b] 1st R-Value represents continuous insulation; 2nd refers to cavity insulation.

[c] SHGC : Solar Heat Gain Coefficient

[d] IECC 2006 represents 100% Home Energy Rating Score (HERS)

[e] Sherman (LBNL 2008) estimates 6 to 8 ACH for typical new home

[f] Visual Inspection sufficient

[g] IRC: International Residential Code

Figure 8. Building energy codes prescriptive requirements for ASHRAE climate zone 3

The analysis on climate zones 2 and 6 (which correspond with the cities Austin, Texas and Minneapolis, Minnesota respectively) was to develop both the site energy consumption of the home at each location, as well as to determine the annual energy cost in dollars. Displayed below in Figures 9 and 10 are the 2 energy consumption graphs generated by BeOpt.

In Austin, it can be observed that the cooling cost is the most significant decrease, which is the anticipated result. This verifies that there are potential savings by using the new duct design. Minneapolis found similar results, though in addition to the reduction in the cost of heating (colder climate), some of the heating converted to supplemental heating during the change. This is significant since supplemental heating reduces the amount of heating required in the overall home, focusing it on living areas through supplemental sources such as body heat. An increase in supplemental heating over regular duct heating is a major cost savings, especially in colder climates.

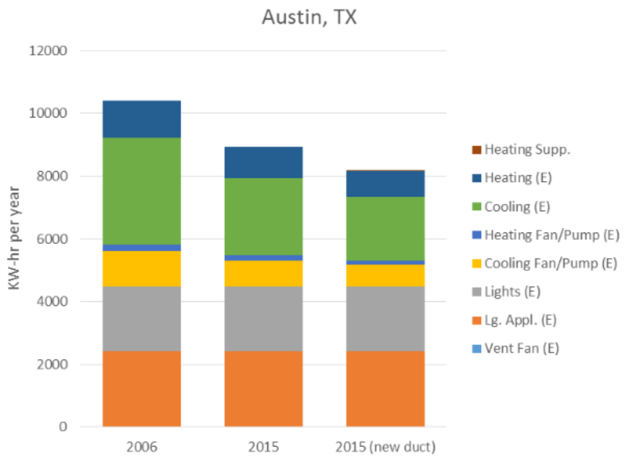


Figure 9. BeOpt energy consumption graph for a home located in Austin, Texas

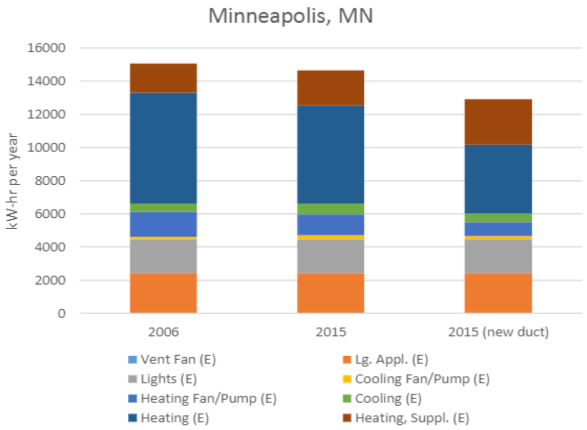
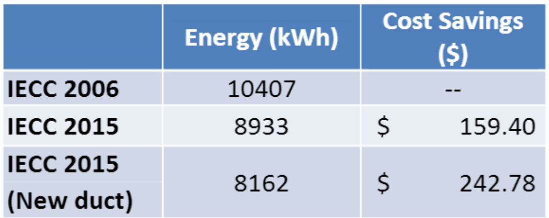


Figure 10. BeOpt energy consumption graph for a home located in Minneapolis, Minnesota

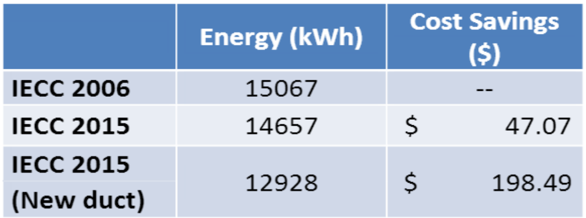
Additionally, BeOpt determined the annual energy cost in dollars. This was a major output we were looking to examine from the results of these tests. As seen in Table VI below, the new design yielded an extra 52% of cost savings per year as compared to the baseline savings associated with increases in code requirements from 2006 to 2015. As for Minneapolis, shown in Table VII, the savings were much more significant when using the new duct. The new design caused a 420% increase in the savings compared to baseline. This is potentially due to the additional supplemental heating shift observed in the simulation that was not present in the hotter climate zone.

Table VI. Energy cost comparison (per year) for Austin, Texas



	Energy (kWh)	Cost Savings ($)
IECC 2006	10407	--
IECC 2015	8933	$ 159.40
IECC 2015 (New duct)	8162	$ 242.78

Table VII. Energy cost comparison (per year) for Minneapolis, Minnesota



	Energy (kWh)	Cost Savings ($)
IECC 2006	15067	--
IECC 2015	14657	$ 47.07
IECC 2015 (New duct)	12928	$ 198.49

Overall, the savings, while relitively large, show that this design would not be possible at the current time due to the high cost of PVC and the initial costs required to alter the current duct designs already set in place. The speculated payback time for the system is around 48 years, which is much higher than the lifespan of the system and thus unreasonable. Potential changes or technological advancements may decrease the cost significantly which would then make the design financially viable.

5. CONCLUSION

The objective of this project was to design a more efficient duct system for residential HVAC units. In particular, it was desired that the duct system capture the energy savings associated with placing the duct in the conditioned space, while still allowing the duct to be placed in the attic. In order to accomplish this goal, multiple Visual Basic computer programs were developed to simulate the R-value associated with various insulation materials used to insulate the duct system. The insulation materials tested included gases, solid insulating materials, and vacuum insulation. Based on the results of these simulations, it was decided to design a vacuum-jacketed PVC duct system.

One of the main questions associated with this design was whether or not it would have the ability to hold vacuum to the desired level over a long period of time. Although, the pressure level could not be reduced to the desired level during the testing process, the results were still promising. After an initial outgassing process, the prototype managed to hold the pressure relatively constant over the course of days. Also, although there was not time to test it, there is currently a patented design that allows PVC to be used in high- and ultra-high vacuum applications. This means that there is a high likelihood that the outgassing problem could be eliminated. The pressure level issue also had a simple solution. All that was required to reduce the pressure level down to the desired value was a better vacuum pump.

One of the main challenges associated with a duct design utilizing vacuum insulation is the structural integrity of the system. This is because pulling vacuum on the annular region of the duct system induces a large pressure difference between the annular region and the surrounding atmospheric air in the attic. This pressure difference manifests itself as essentially a compressive load on the outer wall of the guard of the duct. This greatly limited the materials that could be chosen for the duct system and was one of the main reasons PVC was selected. When using PVC, the hoop stress in the wall of the guard duct was well within the proportionality limit specified by the PPI.

In order to assess the cost required to build an HVAC system using the new duct design, a 2,000 square foot model home was used. Based on this, it was seen that the new PVC duct design cost roughly $4,900 more to construct than the typical sheet metal duct. There are numerous reasons as to why the PVC duct is much more expensive. The main reason is that the vacuum system calls for essentially constructing two separate duct systems in order to create a vacuum in the annular gap.

Finally, BeOpt was used to analyze the energy savings associated with the new duct design. During the simulations, BeOpt was used to simulate the model house using three different setups: 1) 2006 IECC, 2) 2015 IECC, and 3) 2015 IECC with the new duct design. For Austin, Texas, the house modeled with the new duct design resulted in an increase of savings of roughly $85 a month over the baseline savings. This is equivalent to a 52% increase. For the home in Minneapolis, Minnesota, the new duct design resulted in an increase in savings of $151 per month. This is equivalent to a 420% increase in savings.

Overall, the savings, while relitively large, show that this design would not be possible at the current time due to the high cost of PVC and the initial costs required to alter the current duct designs already set in place. The speculated payback time for the system is around 48 years, which is much higher than the lifespan of the system and thus unreasonable. Potential changes or technological advancements may decrease the cost significantly which would then make the design financially viable.

6. REFERENCES

1. 2015 International Energy Conservation Code, Residential Ducts, § 403.3.1, 2015.
2. Frank P. Incropera, David P. Dewitt, Theodore L. Bergman, and Adrienne S. Lavine, *Fundamentals of Heat and Mass Transfer*, 7th edition, New York: John Wiley and Sons, 2011.
3. P. K. Nag, *Heat and Mass Transfer*, 2nd edition, Tata McGraw-Hill Education, 2006.
4. ASTM E84-17 Standard Test Method for Surface Burning Characteristics of Building Materials, ASTM International, West Conshohocken, PA, 2017, https://doi.org/10.1520/E0084-17.
5. Charles A. Grenci and R. Dallas Clayton, *Plastic High Vacuum Piping Components*, United States Patent: 54255264, 1995.
6. 2006 International Energy Conservation Code, 2006
7. 2015 International Energy Conservation Code, 2015.
8. ASHRAE, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, ANSI/ASHRAE/IES Standard 90.1, 2016