INTEGRATED DESIGN LAB
University of Idaho

AN EMPIRICAL IDAHO STUDY ON DUCT SEALING EFFECTIVENESS

RESEARCH STUDY

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Association of Idaho Cities
Office of Energy Resources

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Date
March 20, 2013

Report No.
20130124-01

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Please cite this report as follows: Dunn, J. Van Den Wymelenberg, K. 2013. *An Empirical Study on Duct Sealing Effectiveness;* Technical Report 20130124-01, Integrated Design Lab, University of Idaho, Boise, ID.

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1. Executive Summary

This study used an 11 home sample and a full year of pre and post-measured utility data to quantify the effectiveness of a duct sealing upgrade conducted at the end of 2011. These savings values were also compared to energy simulations that were created for each home based on detailed field measurements from duct pressurization tests conducted before and after the upgrade, which produced an 31.4% average duct leakage improvement. A series of t-tests revealed a statistical significance for the therms savings in the coldest months of pre and post-upgrade utility data. While kWh savings existed between the two data sets, too much randomness from occupant controlled variables (i.e. plug loads, cooking, etc.) overshadowed the effect of the duct sealing. Consequently, savings calculations typically only take into account therms savings for these four months. This produced an average annual 45.83 therms savings, a 4.8% therm consumption savings, a 4.1% overall energy reduction, and a $41.38 cost savings, and a 21.33 year payback. **Table 1** shows these savings amongst other scenarios to provide insight into the sensitivity of the numbers given the parameters of the experiment.

Table 1 -Therms Savings Summary

	Average Savings from Weather Normalized Data	Average Savings from Weather Normalized Data (without outlier)	Extrapolated Savings (without outlier)	Simulated Savings
therm savings	45.83	62.83	87.7	41.2
therm % savings	4.8%	8.4%	9.1%	4.4%
total energy savings	4.1%	4.9%	8.0%	2.7%
cost savings	$ 41.38	$ 50.30	$ 79.19	$ 37.20
simple payback (years)	21.33	14.05	11.15	23.73

The table illustrates that when one of the outliers from the sample, a home that consumed 24% more energy in 2012 post-upgrade, the therms savings increased to 62.83 and represented an 8.4% reduction in overall therm consumption. The "Extrapolated Savings" column shows the result as if all twelve months contained statistically significant savings. This scenario entailed taking the average savings from the weather normalized data (without the outlier) and normalizing it to the amount of heating degree days in the four months of statistically relevant data. Next, this number was applied to the remaining month's heating degree days to calculate the additional potential savings. This method resulted in the best possible scenario of savings given the small sample of the project and the influence of the uncontrolled variables at play. The extrapolations produced a therms savings of 87.7, a 9.1% heating reduction, an 8.0% overall energy reduction, and an 11.16 simple payback period.

Even though the t-test produced statistically significant savings, it is harder to correlate these values to solely the duct sealing upgrade. A regression analysis provided a relatively low (R2=.11) correlation between the weather normalized savings and the measured CFM improvements for each home. Additionally, while **Table 1** shows a close similarity between the average simulated and weather normalized savings, considerable difference existed between the two numbers on each home. These differences balanced out in the average calculation due to the large negative savings of one of the weather normalized data points. The simulated savings were generally lower and suggest that the uncontrolled human behavior variable had a large impact on the savings values of some homes. This, combined with the relatively low impact of duct sealing on overall energy use, obstructs definitive conclusions on the effectiveness of duct sealing on the small data set.

Despite the lack of definitive conclusions, the overall effect of the duct sealing improvement remained relatively small in all savings scenarios. Even considering the extrapolated savings scenario, the simple payback period never dropped below ten years (11.5 years was the shortest). The relatively small savings associated with duct sealing was consistent throughout this research and in many of the literature review references.

2. Introduction

This report builds upon previous research conducted on the residential duct system upgrade process by Penn State University, the National Energy Leadership Core (NELC), Boise State University, the Idaho Division of Building Safety, and the University of Idaho Integrated Design Lab (UI-IDL) in 2011 (Dunn et al. 2012). The original research gathered detailed information on field-testing data for residential duct sealing upgrades and correlated energy savings figures according to home age as part of an improved approach to the home energy audit process. The initial research studied the immediate effect of sealing ducts in unconditioned spaces for a 28 home sample. The research presented in this report examines the longer term effectiveness of the previous duct sealing efforts on a subsample of the 28 homes. Given that a full year has passed since the conclusion of the original duct sealing research a 12-month pre and post-upgrade energy utility data analysis was possible. The goal of this research included using utility data to produce weather normalized, realized energy savings figures for the duct sealing upgrade on Idaho homes. These numbers provide insight into the effectiveness of duct sealing to save energy and reduce utility costs for homeowners in the region. The data also allow for the comparison of realized savings figures to the previous simulated predictions from BEopt energy models in the initial study, as well as other similar field studies from other climates.

2.1. Problem Statement

Aging or poorly installed residential air distribution ductwork can lead to inefficiencies throughout a home’s entire heating and cooling system due to leakage, especially when ducts are not in the conditioned space. The advancement of the residential energy efficiency code (IECC 2009) has mandated duct leakage thresholds for ducts installed outside the thermal envelope in new construction, but minimizing leakage in existing homes represents an opportunity for energy efficiency and utility cost savings. An initial study used field data to inform simulations that predicted savings (Dunn et al. 2012), but empirical savings figures are also needed to help determine duct sealing effectiveness and feasibility.

3. Literature Review

This process began with an examination of existing research which quantified savings from various duct sealing upgrades. These included studies that utilized both simulation-driven approaches for savings calculations and studies that used field data to calibrate simulations, amongst a variety of other means, to extrapolate annual energy savings. Our research more closely aligns with latter approach. However, the literature search did not encounter any studies that conducted a full year of post-upgrade utility data to determine realized energy savings from the duct sealing upgrades.

A recent Building America technical report addressed optimal home retrofit energy efficiency upgrades based on building simulation modeling (Polly et al. 2007). While the report did not recommend duct sealing by itself as cost effective for any of the eight climate simulated, it did recommend duct sealing in combination with duct insulation in multiple optimization packages as cost effective. The study used BEopt (Christensen et al. 2006) as the performance analysis software, and assumed 15% as their pre-upgrade leakage fraction as a percentage of total supply airflow. Post-upgrade duct leakage assumed a 50% reduction. These figures yielded savings within the eight reference cities from 1.7-4.0% of total annual source energy.

An article in ASHRAE Transactions evaluated the effectiveness of duct sealing in residential applications (Yuill and Musser 1997). These studies identified that approximately 30-40% of the energy delivered through air distribution systems are lost, and that these losses occur equally between air leakage and conduction losses. The research included performing a duct pressurization test of seven homes in Pennsylvania while monitoring the homes' energy consumption for one month prior to enacting the duct sealing upgrade. Next, the study re-tested the homes post-upgrade and conducted an additional month of energy monitoring. This information was used to calibrate a simulation model to correct for weather differences and predict annual energy and cost savings. The study concluded that only one of the five final houses in the study showed significant energy savings that could be associated with the upgrade. These predicted savings were based on the average 16% post-upgrade reduction in leakage. The study acknowledged the problems of the final analysis due to the small sample size, variable pressures in the house and duct system, and the variety of home configurations tested. For example, the study looked at homes that had supply ductwork configured in both the basement and attic. The one home that showed savings had ductwork in an unconditioned attic, but the other homes in the sample with the same configuration did not reveal significant savings.

The Regional Technical Forum's (RTF) Performance Tested Comfort Systems (PTCS) subcommittee conducted a simulation-based duct sealing performance study in 2011 (RTF 2011). The research used SEEM software (DOE 2011) to analyze the effects of duct sealing on a tight range of home sizes and typical HVAC system types. Systems analyzed included an average heating system, an electric forced air furnace system (with and without a central furnace), and an electric heat pump system. The study also conducted this analysis over three different heating zones that were weighted by the SEEM analysis. The zone that resembled Boise, Idaho's climate the closest was heating zone 2, which contained a weighted analysis between simulations ran for Boise, Kalispell, and Spokane. The study assumed a 15% supply duct leakage fraction of total supply air, and a 10% return duct leakage fraction. Post-upgrade assumptions included a 67% improvement for both supply and return leakage. The SEEM simulations translated this leakage improvement number and predicted an annual heating savings of 2,072 kWh (70.6 therms) for the average heating system and 32 kWh for cooling system savings. Finally, the research used a regression fit cost model with over 1,600 homes to determine sealing costs based on the amount of leakage improved on each house. This not only informed the pre and post-leakage assumptions for the model, but it also provided a predicted average cost of $600 for duct sealing services.

A study in Arkansas used the "pressure pan" technique to gather pre and post duct leakage data on 18 homes in Arkansas. This procedure allows for quantification of leakage while providing direct feedback that can guide sealing efforts. The study looked at both heat pump and residential gas furnace systems, and produced an average baseline duct leakage of 21.6%. Savings were calculated through metering daily consumption and correlating these figures to outside air temperatures. This provided data used to create a regression that was extrapolated to annual heating energy savings, which were on average 19.7% for the homes with gas furnaces.

The studies reviewed showed great variation in data gathered on duct pressurization method, leakage improvements, and predicted or realized energy savings. No research was found that conducted pre and post-data acquisition and weather normalization to arrive at the realized annual savings from duct sealing upgrades. This type of information is difficult to attain and at least two years of data are needed for accurate analysis. Finding homes that have only undergone the duct sealing upgrade, and had no other modifications, during the analysis period exacerbates the problem of conducting a scientific experiment to quantify savings. Additionally, zero of the studies compared predicted energy savings from simulation to the realized savings figures. More empirical, climate specific, and weather normalized data are needed for specific climate regions that address the impact of duct sealing efforts on energy consumption and utility costs. Simulation data exists and can be used as a gauge for effectiveness, but additional comparisons between simulated data and empirical data would help lend confidence to the predictive savings numbers of the software.

4. Methods

4.1. Research Questions

The following research questions focus on the effect of weather normalization on the baseline data, the quantification of energy and cost savings from the duct sealing upgrades, and differences between simulation predictions and realized savings. One of the questions also hopes to provide insight on how to account for the variations in energy use from the duct sealing upgrade and potential behavioral changes unaccounted for in the study.

- What is the weather normalized, realized energy and cost savings from the duct sealing upgrade?
- What is the correlation between the duct savings numbers and the realized savings?
- How close were the BEopt predicted savings to the weather normalized, realized energy savings?
- How much effect does weather normalization have on energy consumption?

4.2. Home Sample

The initial study (Dunn et al. 2012) gathered a random 28 home sample from three different home age ranges (1970s, 1980's, and 1990s) for a subdivision in the west part Ada County within the larger Treasure Valley region around Boise, in Idaho. The study sought to limit the physical characteristics of the homes to the following:

- Approximately 1200-1800 square feet
- Single story homes
- 1970s, '80s or '90s vintage
- Subdivision rather than custom home
- Vented crawl space
- Minimal HVAC system modifications
- Gas or electric forced-air furnaces heating type

Next, the research team recruited homes for the study by following a series of steps:

- Identified subdivisions built within target timeframe within Ada County
- Hand delivered postcards to homes that appear to meet study requirements
- Interested homeowners then completed an online prescreening survey
- The online survey captured initial home characteristics (such as HVAC type) and contact information for the homeowner. The research team then emailed the homeowners and notified them that home has pre-qualified
- Phoned homeowners to schedule survey of homes qualified for Simplified Analysis
- Homeowner completed utility release forms

For this follow up study, the authors re-approached the 28 homeowners from the initial study via email, phone, or site visits. Homeowners were asked to participant in the follow up study if they had not undergone any additional upgrades since the study occurred and did not experience any major occupancy changes. Homeowners then signed an additional utility release waiver for the year of 2012 and these data were compared to the pre-upgrade utility data gathered in the first study for analysis. Due to changes in home ownership and presence of duct insulation and thus zero sealing improvement (see section 4.3 Testing Procedure for more information), only 16 of the original 28 homes were eligible for the follow up study. Out of these 16, the research team secured signed utility release waivers for 11 homes within the time constraints for this research.

4.3. Testing Procedure

Once the final 28 homes were selected for the initial study, the Idaho Division of Building Safety led the field data collection effort. The research team visited each home to collect detailed information on the home required for the BEopt energy models. This also included conducting a duct pressurization test for the specification of baseline duct leakage in the models. The research team employed a standard duct pressurization protocol to gather total system leakage rates at 25 Pascals of pressure difference. The team operated under the assumption that any leakage measured represented airflow directly to the outside, mostly because the location of the supply and return ductwork was in an unconditioned crawlspace and attic.. The pre-measurement, duct sealing, and post-measurement process was limited to a three hour window designed to represent the typical timeline spent by a two-person team conducting a similar upgrade. Thus, time was spent sealing supply ductwork to maximize the time spent on site and achieve the biggest reduction in CFM leakage And the team did not make an effort to seal return ductwork. Spending time in attics could also be time-consuming, disrupt existing insulation, and cause damage to sheetrock and other interior finishes. Return air ductwork grill and furnace connections were not typically readily accessible in most houses. Finally, the team did not seal homes with insulated ductwork. The homes showed acceptable duct leakage values from the pre-upgrade duct pressurization test and attempting to seal the ductwork would require too much work to dismantle the insulation, seal the ductwork, and then reinstall the insulation.

The follow up study did not include any additional field testing. **Table 2** shows the pre-and-post-leakage values in a variety of metrics for only the 11 final homes in the follow up study. The average improvement equaled 31.4% and the average final CFM of leakage as a percentage of floor area equaled just above 10%. It is important to note that some of the pre-existing leakage values are relatively low and did not necessarily warrant a duct leakage upgrade. These homes were part of the initial study (Dunn et al. 2012) and were kept in the follow up research to increase sample size.

Table 2 - Pre and Post Home Leakage Characteristics

House #	Pre Upgrade Leakage (CFM @ 25PA)	Pre Upgrade Leakage as a % of floor area	Post Upgrade Leakage (CFM @ 25PA)	Post Upgrade Leakage as a % of floor area	total cfm saved (CFM @ 25PA)	% CFM saved improvement
BID_30	630	34.8%	480	26.5%	150	**23.8%**
BID_24	460	27.9%	362	21.9%	98	**21.3%**
BID_46	258	18.4%	150	10.7%	108	**41.9%**
BID_25	190	13.6%	94	6.7%	96	**50.5%**
BID_44	171	10.0%	121	7.1%	50	**29.2%**
BID_56	138	9.4%	98	6.7%	40	**29.0%**
BID_63	122	8.6%	85	6.0%	37	**30.3%**
BID_66	161	12.1%	120	9.0%	41	**25.5%**
BID_40	224	11.1%	184	9.2%	40	**17.9%**
BID_48	165	10.9%	144	9.5%	21	**12.7%**
BID_53	605	45.4%	219	16.4%	386	**63.8%**
Avgerage	284	18.4%	187	11.8%	97	**31.4%**
Median	190	12.1%	144	9.2%	50	**29.0%**

4.4. Simulation Approach

The research team used BEopt V1.3 (DOE 2011) as the software program for residential energy simulation. The Department of Energy developed this software as a front end with optimization capability for its DOE 2.2 and EnergyPlus simulation engines. For duct leakage modeling, BEopt does not readily accept the field testing results (CFM leakage at 25 Pascals of pressure difference) as inputs. Instead, BEopt defines duct leakage as a fraction of leakage for both supply and return as a percentage of total air handler flow. Consequently, the research team used the baseline model outputs to determine the max airflow of each home. This number was then used in conjunction with the pre and post-upgrade leakage numbers to calculate the modeling inputs using the default leakage distribution in the BEopt software between supply and return components. This method essentially divided the field testing results, (CFM at 25 Pascals), by the modeled baseline maximum airflow with no measured pressurization (CFM). While these two units are not directly comparable, the pressure difference of the field testing is intended to represent pressurization during air handler operation. Additionally, time was not taken to calibrate the simulations to baseline utility data. Data from the initial site visits and testing were used primarily to specify the models, and any information that was not readily available referenced Department of Energy's Building Simulation Protocols (Hendron and Engebrecht 2010) for inputs.

Once baseline and post-upgrade models were developed, the research team ran the simulations with typical meteorological year (TMY) data to determine the impact of the upgrade. It is important to note that the intent of simulations for the initial study was to predict the annual savings for the upgrades in lieu of any post-upgrade utility data. The intent of the follow up study was to compare these "typical" predictions to the realized, measured savings. Therefore, the energy models were not re-run with 2010 and 2012 weather data to directly compare the simulations against the pre- and post-upgrade measured utility data. More importantly, the analysis aimed to compare the accuracy of the total energy reduction and total heating reduction percentages from a typical energy modeling process.

4.5. Analysis

The analysis plan generally included the following steps once homeowners provided post-upgrade utility consumption to the research team:

1. Define variables and control strategy for analysis
2. Conduct weather normalization on the two years of utility data
3. Run T-tests to determine if a statistically significant difference exists between the weather adjusted baseline sample data and post duct sealing data
4. Compare the weather-adjusted baseline to the post-upgrade utility data for relevant metrics
5. Use correlation analysis to determine the extent of the effect of duct sealing on any energy savings found
6. Compare simulated savings predictions to realized savings numbers

The analysis aimed to determine the effect of duct sealing on the homes, so the upgrade served as the independent (explanatory) variable in the study. Next, consistent home sample design (single storey, ducts in the crawl space, etc.) and weather normalization between the two utility years helped to reduce the number of confounding uncontrolled variables. For the follow up study, the homeowners were given the opportunity to contribute only if their homes had not undergone any additional energy upgrades or large-scale occupancy changes. This also helped limit the uncontrolled variables that revolve around the inherent variation between day-to-day home operations, which may have significant effects on home energy consumption. **Table 3** summarizes the types of variables present in the experimental study. As the table suggests, there are still many factors that were uncontrolled that may account for the differences in energy use between the two utility years, even if the design of the experiment controls weather variation.

Table 3 - Summary of Experimental Variables

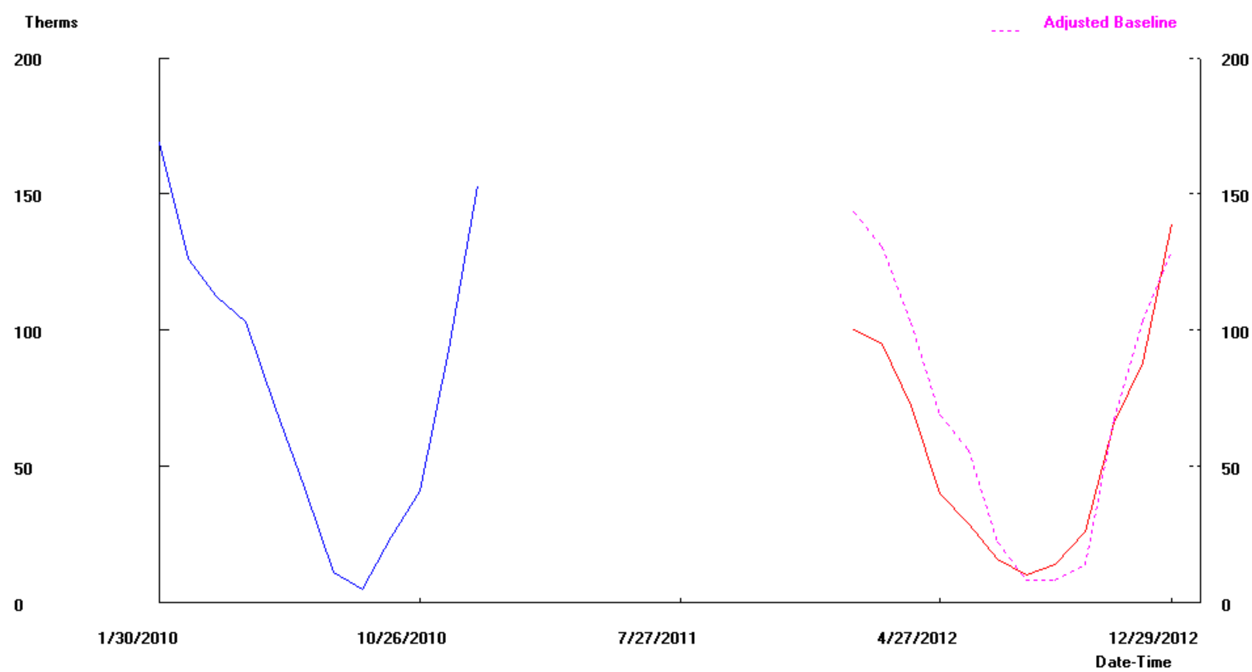
indpendent variables	dependent variables	controlled variables	Uncontrolled Variables
duct leakage improvement	energy consumption	weather variation	plug load usage
		large-scale occupancy changes	cooking
		home size and type	lighting operation
		duct location and configuration	thermostat operation
		amount of energy upgrades	length and frequency of hot water usage
		HVAC system type	operable window operation
			small scale behavioral changes
			duct material
			home age

4.5.1. Weather Normalization

The research team used EnergyExplorer (DOE 2011) for the weather normalization process. The program was designed for the analysis of building and facility energy use data with time series plotting capability. Additionally, trends can be analyzed in the software with multi-linear regression in a variety of different equation-fit models. First, the pre and post-utility data were converted to files that could be imported into the software and viewed as time series variables. Next, the program imported pre-built weather data for Boise, Idaho that spanned across multiple years including 2010 (pre-upgrade) and 2012 (post-upgrade). The program then merged the two files together to plot energy consumption data, per fuel type, against outside air temperature. The model applied a three-parameter change point regression to correlate these two types of data. A three-parameter change point was utilized for the regression to take into account energy use that is non-linearly correlated with an independent variable. Frequently, energy use is influenced by more than one variable, such as duct leakage (the independent variable) and uncontrolled variables associated with occupant usage. Additionally, two of the homes in the study contained electric heat pumps for space heating. These homes used a four-parameter change point regression because the consumption sloped in different directions for both heating and cooling operation. This typically resulted in a much better R^2 value and an equation that more closely matched the data.

The regression equations allowed the energy consumption characteristics of the 2010 year, i.e. energy use, to be calculated as a product of outdoor air temperature. This factor was then applied to the 2012 weather data and formed the weather normalized, or adjusted baseline, against which the 2012 utility data was compared. Any savings from this action represented the weather normalized savings for the duct sealing upgrade. **Figure 1** shows this process visually in EnergyExplorer for a random house in the sample. The program plots the continuum of utility data across the 2010 and 2012 year, while also plotting the newly adjusted 2010 baseline against the 2012 utility values (shown as the dotted line). Any area in between the two lines represents the calculated savings or penalty post-upgrade. The program also includes the error margin of the adjusted baseline and the R^2 value of regression lines. Once the weather normalized savings were calculated for the 11 homes, the analysis included a second regression between these values and the duct leakage CFM savings from the initial study. The R^2 value of this regression begins to provide insight on whether or not the savings were the result of the upgrade, or something else, such as behavior changes of the occupants.

Figure 1 - Utility Data With Adjusted Baseline



4.5.2. *T-Tests*

After using EnergyExplorer to create weather adjusted baselines for each of the eleven homes, t-tests were conducted to determine if a statistically significant difference existed between the 2012 utility data and the weather normalized baselines. The analysis used a probablilty value of .1 and below to determine statistical significance. A one-tailed, matched-pair t-test on the yearly kWh total, therm total, and combined kBtu was conducted. By splitting the t-tests into the fuel types, the t-tests had a better chance of showing significant difference given the higher potential for the kWh fuel type to vary with occupant behavior and the therm fuel type to vary with outdoor air temperature. It is reasonable to assume that the duct sealing would affect the therm fuel type more and thus potentially yeild a more favorable t-test result. However, **Table 4** shows that the t-test failed under all three of these annualized conditions. The "therms only" probability value (p-value) is lower than that of the kWh value, but the fact that the total kBtu value is lower still suggests that some offsetting may be occurring when the two fuels are combined together for analysis. While this shows the best probability value, it is still slightly too high for the 2012 data to be deemed significantly different from the baseline data. This reflects, once again, the large variability within the small sample, likely due to occupant behavior variability.

Table 4 - Annual Aggregate Fuel Type T-Test Results

	Pre and Post Data Set (n=11)		
	kWh only	therms only	total kBtu
Probability Value	0.32	0.22	0.16

It was also hypothesized that the greatest difference due to the duct sealing may be found during the winter months, given less potential confounding occupant behavior variance. Therefore, the team also conducted analyses on a month-by-month basis to determine if any of the months showed statistical significance between the two conditions. **Table 5**, confirms this hypothesis and reveals that the coldest months have a p-value of less than .1, which indicates a significant difference during the months when the duct sealing would influence therm consumption the most. Any calculated therms savings in further analysis result only from these coldest four months. Any kWh savings will not be included, given that neither of the monthly kWh values fell under the required .1 p-value.

Table 5 - Monthly T-Test Results

	pre and post monthly totals (n=11)			
		kWh	therms	kBtu
probability value	january	0.31	0.07	0.08
	february	0.19	0.06	0.06
	march	0.29	0.8	0.63
	april	0.33	0.93	0.81
	may	0.36	0.79	0.66
	june	0.11	0.35	0.10
	july	0.37	0.11	0.22
	august	0.37	0.03	0.10
	september	0.12	0.63	0.19
	october	0.28	0.23	0.17
	november	0.23	0.10	0.05
	december	0.26	0.08	0.01

The last step of the analysis included comparing the simulated energy savings to the weather normalized savings from the previous steps. The magnitude of this difference could lead to multiple conclusions, depending on whether or not the savings align with the predictions or vary significantly. Since the model controls all variables except the duct leakage independent variable, one should expect the realized savings to be similar to the predicted savings or contrast greatly due to occupancy variability.

5. Results

5.1. Weather Normalization

A simple heating and cooling degree day calculation for the 2010 and 2012 weather year serves to provide a quantifiable metric to compare different years of weather. According to Weather Data Depot (EnergyCap 2013), the city of Boise, Idaho's heating degree days at a 65 degree Fahrenheit base temperature decreased from 5081 to 4920 in the two study years. In other words, the city was 3% colder in 2012 than in 2010. For cooling degree days, the value increased from 910 to 1163, a more substantial 28% increase. The data show that the two years were pretty similar in heating, and moderately different in cooling. However, to understand this impact on the HVAC energy consumption for the homes, a more sophisticated analysis is required. **Table 6** shows the difference in the total kBtu between 2010 utility data and the adjusted 2010 baseline from EnergyTracker. While the average difference is only 2.8%, this is more than half of the average savings from the **non-normalized** data (5.3%). Luckily the 2010 heating degree days did not differ substantially from the 2012 data (3% difference). .

Table 6 - Weather Normalization Effects

House #	2010 Baseline kBtu	2010 Adjusted Baseline	% difference
BID_30	169192.78	168032.38	0.7%
BID_24	127400.54	120389.64	5.5%
BID_46	115040.49	113451.60	1.4%
BID_25	67243.70	68216.12	-1.4%
BID_44	89192.92	87558.55	1.8%
BID_56	81799.29	77442.16	5.3%
BID_63	86546.67	84962.77	1.8%
BID_66	121500.85	112597.79	7.3%
BID_40	114053.41	118857.36	-4.2%
BID_48	98726.44	99039.29	-0.3%
BID_53	144846.93	140826.65	2.8%
Average			1.9%
Mean			1.8%

It is important to note that some homes show an increase in energy consumption while some homes show a decrease. This inconsistent result may be due to multiple factors. First, the specific equipment or configuration of the homes might cause each to respond slightly differently to weather. Additionally, **Table 7** shows the R^2 values of the regressions by fuel type and the % error values for each adjusted calculation. The average R^2 value for the kWh adjustments were .74 versus the therms correlation which equaled .90. The kWh regression values, despite using the three and four-parameter change point regression, are low compared to the therm adjustments. Since the kWh consumption of the homes is contingent upon lighting, cooking, miscellaneous plug loads, and cooling, this dependent variable is possibly influenced more by occupant behavior and less by the outside air temperature. Additionally, cooling energy makes up a small percentage of the kWh distribution when compared to the aforementioned end uses. This is in direct contrast with the therm calculation's regression, where the weather dependent variable (space heating versus water heating) makes up a large portion of the end use and thus would reasonably yeild better correlation with the outside air temperature. The kWh calculation's low R^2 value, in conjunction with a larger potential % error margin due to occupant behavior, could explain the variation in weather normalization effect.

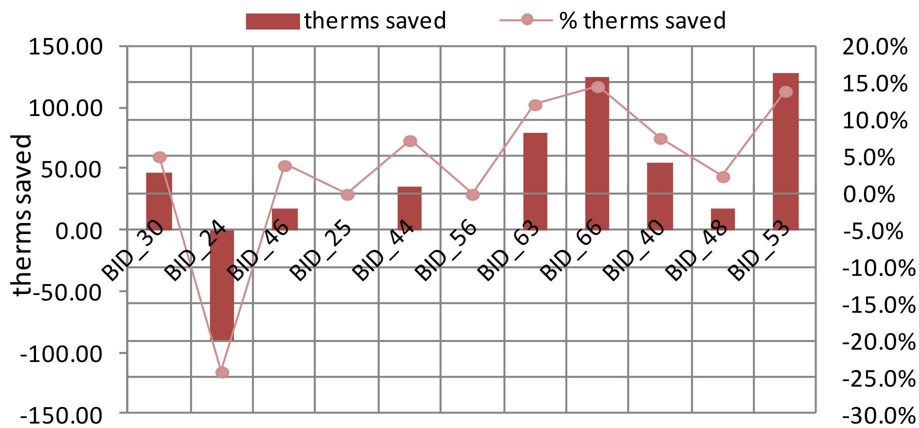
Table 7 - R-Squared and % Error Values for Weather Normalization

kWh	R2	% error (+/-)	therms	R2	% error (+/-)
22867	0.8	11.40%	899.50	0.93	10.40%
24339	0.77	8%	373.20	0.71	38%
20018	0.51	5%	451.20	0.96	13%
19993	0.94	9%	x	x	x
11608	0.73	11%	479.20	0.98	9%
22697	0.66	14%	x	x	x
5882	0.85	13%	648.50	0.92	12%
7975	0.66	10%	853.30	0.95	10%
14024	0.81	17%	709.60	0.77	23%
7066	0.73	19%	748.80	0.92	17%
14477	0.7	11%	913.70	0.93	9%
average	0.74	12%	675.22	0.90	16%
median	0.73	11%	709.60	0.93	12%

5.2. Weather Normalized Energy Savings

Analyzing energy savings can be broken down only for the therm savings because it showed the significant statistical difference for the four coldest winter months. **Figure 2** describes the weather normalized energy and cost savings for the therm energy usage for only these four months, which contains end use consumption data from both space heating and water heating. BID_25 and BID_63 do not have therm savings because both homes used an electric heat pump for space heating. The chart shows a relatively low average therm savings (45.83 therms) and percent savings (4.8%). However, if the analysis removes the outlier from house BID_24, which had the lowest R^2 value of .71, the average therm savings increases to 62.83 and the average savings jumps to 8.4%. Similarly, the average cost savings increases from $41.38 to $50.3 with a range of -$81 to $115.60, or $15.89 to $115.60 without the outlier In terms of total energy, the therms savings translate into an average 4.1% annual energy savings and increases to 4.9% without the outlier. The negative therm savings of house number BID_24 may be attributed to random behavior changes in the house that the study could not control.

Figure 2 - Weather Normalized Therm Savings

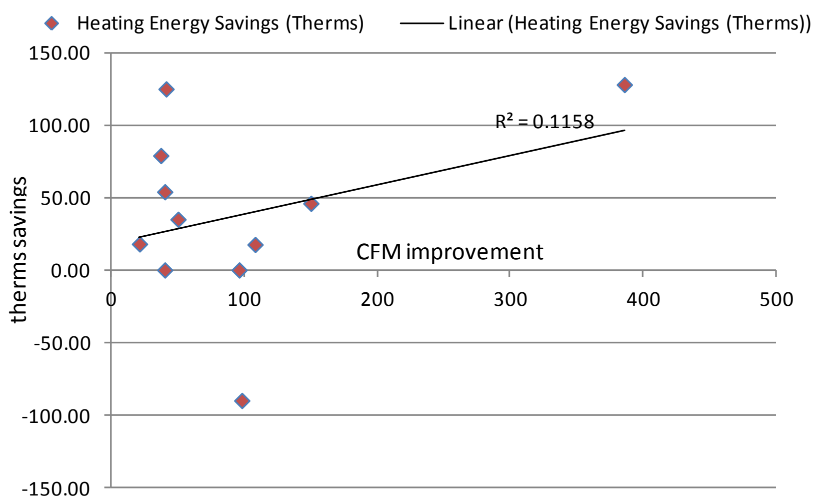


House #	therms saved	% therms saved	kBtu saved	% total energy reduction	Therm Cost Savings
BID_30	46.00	5.1%	4603.08	2.7%	$ 41.54
BID_24	-90.10	-24.1%	-9016.03	-7.5%	$ (81.36)
BID_46	17.60	3.9%	1761.18	1.6%	$ 15.89
BID_25	na	na	na	na	na
BID_44	35.00	7.3%	3502.34	4.0%	$ 31.61
BID_56	na	na	na	na	na
BID_63	79.00	12.2%	7905.29	9.3%	$ 71.34
BID_66	125.00	14.6%	12508.36	11.1%	$ 112.88
BID_40	54.00	7.6%	5403.61	4.5%	$ 48.76
BID_48	18.00	2.4%	1801.20	1.8%	$ 16.25
BID_53	128.00	14.0%	12808.56	9.1%	$ 115.58
average	45.83	4.8%	4586.40	4.1%	$ 41.39
median	46.00	7.3%	4603.08	4.0%	$ 41.54

5.3. Correlating Duct Sealing to Energy Saving

Given the complexity of the uncontrolled variables at play, some type of analysis was needed to determine to what extent the duct sealing improvement figures had on the statistically different energy savings (or penalties). The research team conducted a series of regressions on four months of heating energy savings, total yearly cooling energy savings, and total yearly kBtu savings in relationship to the absolute CFM saved from the field testing results. R^2 values serve as the main indicator of whether or not savings can be attributed to duct sealing, or to the behavior variance within the homes in 2010 versus 2012. **Figure 3** shows that when using a simple linear regression, the research produces a low R^2 value of .11 for heating savings correlation. Removing the aforementioned outlier, this value increase slightly to .22. Either way, the values do not show a strong correlation between the heating energy savings and duct sealing values. The R^2 values for the yearly cooling and total kBtu savings are even lower, which is to be expected as they are arguably more sensitive to occupant behavior than the heating energy. These figures can be found in the appendix for reference.

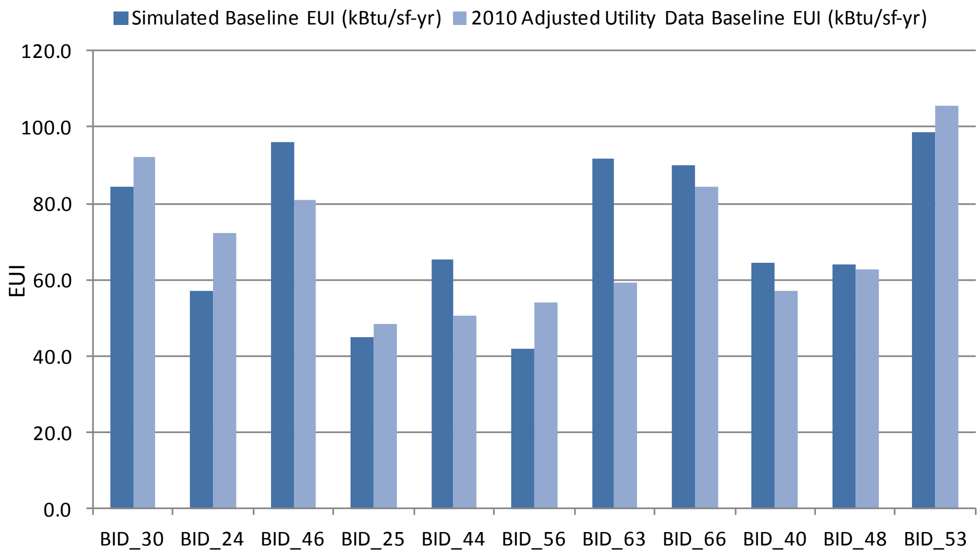
Figure 3 - Heating Energy Savings vs. Duct Sealing Improvement



5.4. Simulation Comparisons

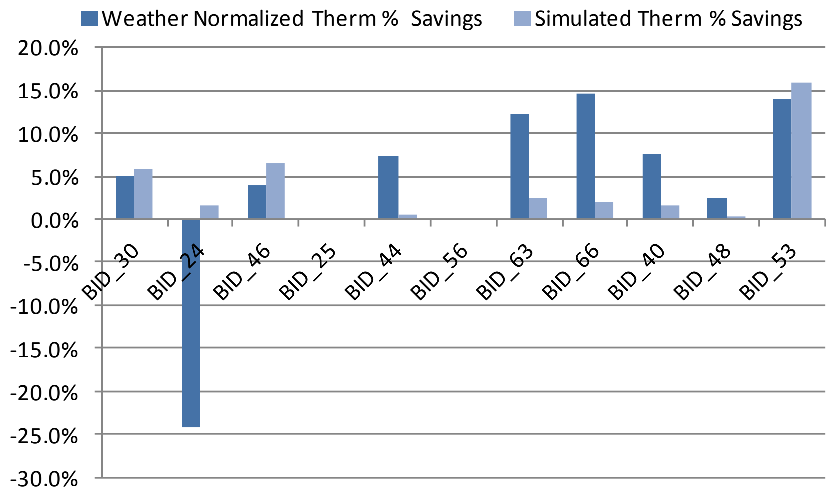
Finally, the last phase of the analysis included comparing the simulated savings to the weather normalized savings. However, given the results of the regression analysis and the variation of the data, this comparison represents more closely what the savings values should have been versus how well the simulations predicted the "actual" savings. This analysis looks at two types of metrics: absolute savings per unit and percentage reduction. The absolute savings per unit can be helpful when looking at simple paybacks according to the simulation, while a percentage reduction comparison to the realized savings can provide insight on how effectively the simulation tool can predict savings from this type of upgrade. **Figure 4** shows the difference between the energy use intensity (kBtu/sf-yr) of baseline simulation models and the baseline utility data. An average 17.2% variance is reasonable given that the models did not undergo calibration efforts.

Figure 4 - Simulated vs Utility Baselines



Next, **Figure 5** shows the difference between simulated savings predictions for the percent reduction in therm consumption between the models and weather normalized savings. The averages are similar for the weather normalized savings (4.8%) and the modeled savings (3.4%), but the data shows a large variation between the magnitutde of the values. A paired t-test showed a p-value of .74, which argues that the differences between the two groups are random in nature. Additionally, the small savings for some of the models can be explained by the low CFM saved during the duct sealing process. A polynomial regression between the modeled total kBtu savings and the amount of duct leakage CFM saved produced a high R^2 value of .93. This is to be expected as the leakage CFM was input directly into the simulations. The data reinforces the idea that the duct sealing savings have a relatively small effect that can be overshadowed by other behavioral issues in the home. The difference in values starts to suggest the magnitude of effect that behavior has in the sample. For example, homes BID_63, BID_66, and BID_40's weather normalized savings are substantially higher than the simulated savings. However, the simulation's duct sealing inputs were input directly from the CFM improvement numbers measured by the field tests, which were amongst the lowest for these three homes.

Figure 5 - Modeled kBtu Savings vs. Weather Normalized Savings



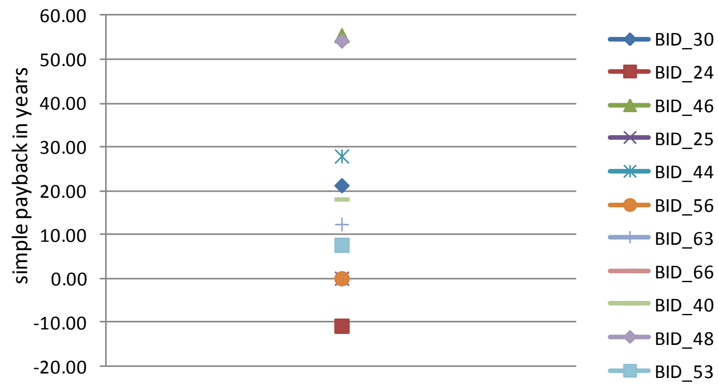
House #	Weather Normalized Therm Savings	Simulated Therm Savings	Weather Normalized Therm % Savings	Simulated Therm % Savings
BID_30	46.00	70.00	5.1%	6.0%
BID_24	-90.10	9.00	-24.1%	1.6%
BID_46	17.60	61.00	3.9%	6.6%
BID_25	na	na	na	na
BID_44	35.00	4.00	7.3%	0.6%
BID_56	na	na	na	na
BID_63	79.00	24.00	12.2%	2.4%
BID_66	125.00	18.00	14.6%	2.0%
BID_40	54.00	15.00	7.6%	1.6%
BID_48	18.00	2.00	2.4%	0.3%
BID_53	128.00	147.00	14.0%	15.8%
average	45.83	38.89	4.8%	4.1%
median	46.00	18.00	7.3%	2.0%

5.5. Cost Savings and Simple Payback

The follow up study utilized the cost data gathered in the initial study to calculate simple payback on the weather normalized savings. Three cost quotes from local contractors were gathered for a two-person team to test and seal supply ductwork in a crawl space within a three-hour window of time. The average cost equaled $883 dollars and broke down into $227 for the duct pressurization testing and $657 for the sealing. This value is close to the $600 duct sealing cost of the Regional Technical Forum's findings reported in the literature review above. **Figure 6** shows a wide spread of simple payback periods given the range of relatively small savings from the weather normalized values. All cost savings were based on the average cost per therm, which came directly from homes' energy bills. Consequently, the $.90 per therm includes the service fees and other arterial costs. Given the wide range of savings, the chart shows simple payback periods from 7.64 years to 55.56 years, with an average 21.33. If only the cost of the duct sealing is considered the range is 5.6 to 41.3 years. These ranges do not include the one negative payback value.

Figure 6 - Cost Savings and Payback

House #	Cost Savings	Simple Payback
BID_30	$ 41.54	21.26
BID_24	$ (81.36)	-10.85
BID_46	$ 15.89	55.56
BID_25	na	na
BID_44	$ 31.61	27.94
BID_56	na	na
BID_63	$ 71.34	12.38
BID_66	$ 112.88	7.82
BID_40	$ 48.76	18.11
BID_48	$ 16.25	54.33
BID_53	$ 115.58	7.64



6. Discussion

6.1. Significance and Correlation

The intended conclusions were to quantify the effectiveness of duct sealing and attach a reliable energy and cost savings value to the upgrade for regional homes based upon year-long measured data. Not surprisingly, the small sample size, along with variability of energy use likely due to occupant behavior, and the relatively small effect of duct sealing all obstruct definitive conclusions. However, the study attempted to mitigate the effects of these three confounding factors and produced statistically significant results for energy savings associated with the coldest winter months, and the magnitude of these results reasonably aligned with simulation outputs and literature review references.

The t-tests revealed that while aggregate yearly energy savings did not show statistical significance for aggregate energy usage, a month-by-month analysis showed significant differences for the times that were critically important to saving energy. In the local climate of the homes sampled, duct sealing will have the greatest effect in heating savings during the winter months, and the additional t-tests revealed that January, February, November, and December all showed significant differences and thus warranted for energy savings analysis. Analysis found that duct sealing saved an average 45.83 therms annually, representing 4.1% of the total energy, 4.8% of gas consumption, and $41.39 in cost savings.

These values would increase if the research design would have been better able to control for several confounding variables. Obviously, a larger sample size would improve the statistical power, addressing some of the human behavior variance in the data, and would potentially yield 12 months of statistically significant differences . It is arguable that 12 months worth of energy savings indeed exist, not just during the coldest months. One possible route to alleviate this issue involves normalizing the average therms savings from the four months by heating degree day, and applying this value to the heating degree days of the other months in 2012. This theoretically creates a heating degree day-normalized savings rate established by the study to be significant, and extrapolating it to months that did not pass the t-test. An increase in annual therms savings from 45.83 to 63.98 (a 28% increase) is possible using this method.

Second, the average duct sealing improvement for the sample of eleven homes equaled 31.4%. This is below the 50% recommendation by the RTF (RTF 2012) and the 67% simulated by the Department of Energy simulation study (Polly et al. 2011). Two of the homes even dipped below 20% improvements and started out with an initial leakage that was around 10% of the floor area. Duct sealing may not have been appropriate for these homes given the relative tightness of the systems. However, the initial study sought to classify duct leakage potential by home vintage rather than by leakage fraction. Consequently, applying duct sealing to a wide sample of homes across different age groups helped determine these correlations. These homes were kept in this follow up study to help increase sample size. If a larger sample were available, the study could be limited to homes with at least a 25% leakage improvement. This would limit the study to homes that have only been subject to “effective” duct sealing. However, this brings up additional questions about how much initial leakage warrants a duct sealing procedure, and introduces the risk associated with paying for only a duct sealing test without applying the upgrade.

Regardless of the low savings, the average 45.83 therms saved during the four coldest months is close to the Regional Technical Forum’s 70.6 therms saved from their SEEM simulation study. The extrapolated 63.98 savings in the study is closer still to this number. The 45.83 therms saved translates to an annual $41.39 dollars and an average simple payback of 21.33 years. However, the length of the payback period is sensitive to individual home and upgrade cost. If the Regional Technical Forum’s average cost is used ($600) with the average cost savings without the negative outlier ($54.58), the resultant payback is a much more favorable 11 years. Further yet, if the average savings is used without the outlier and the extrapolated savings is used, it results in an annual savings of 75.3 therms and a 8.82 year payback. However, none of these cost scenarios reach a five year simple payback, which can be a general target for serious homeowner consideration. The study was not able to show a favorable payback for the duct sealing upgrades based on the data from the small home sample.

6.2. The Importance of Modeling

Even though the study found statistically significant savings, a low correlation exists between the improved leakage CFM with the weather normalized savings. It is possible that the savings were the result of slight behavioral changes in the homes and not the duct sealing upgrade. The monthly t-test results help prove that the savings were not random, but the R^2 value between the duct sealing CFM savings and the weather normalized savings was too low to attribute savings to the upgrade (R^2=.11). Too many uncontrolled behavioral variables exist that can potentially overshadow the relatively small savings potential of duct sealing. As mentioned earlier, this is especially true with any cooling savings due to its small share of kWh usage when compared to other occupant-driven end uses such as plug loads and cooking. This type of empirical study has several difficult to control variables, and given that it spanned over three years only amplifies the potential noise in the data.

Given the difficulties in experiment of this nature, the true value of energy modeling can not be understated. The ability for a simulation to control all occupant-dependent variables and isolate energy efficiency measures is invaluable, as it's nearly impossible to replicate in field studies. Additionally, since the simulations savings results show a strong correlation (R^2=.92) to the leakage numbers, the outputs can start to provide insight into whether or not the realized savings came from the upgrade or behavior. Even though the average simulated savings (4.4%) was very close to the average weather normalized savings (4.8%), a t-test of the two sets of data showed a random relationship (p=.82). The -24% savings for home BID_24 brings the two averages together in an artificial way. The two methods also show a large discrepancy between homes BID_63, BID_66, and BID_40, where the weather normalized savings is much larger than the simulated savings despite a low actual CFM savings. If we trust the simulations, then a large portion of the weather normalized savings likely came from behavioral variance and not the duct sealing upgrade.

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8. Appendix

Figure 7 - Regression Analysis for Yearly kWh Savings

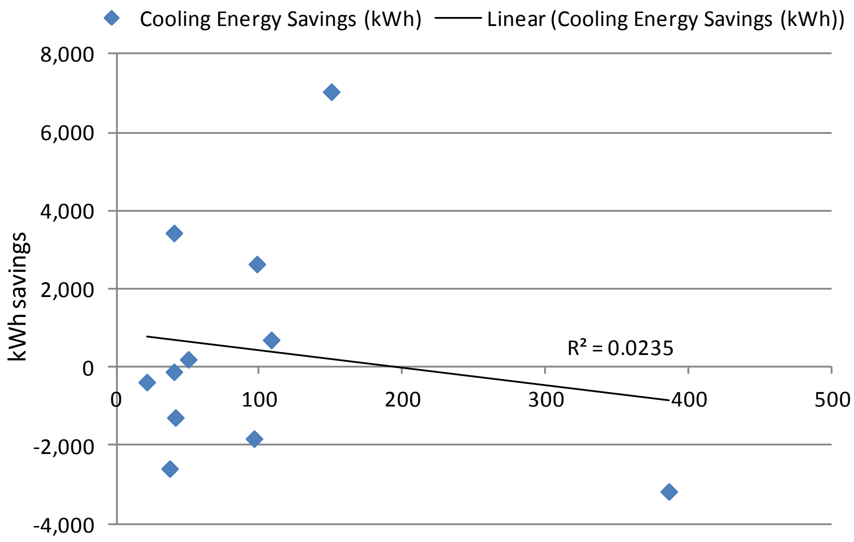

Figure 8 - Regression Analysis for Yearly kBtu Savings