ENERGY LOSSES AND OPERATIONAL COSTS OF RADON MITIGATION SYSTEMS

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ABSTRACT

Energy losses and operational costs of radon mitigation systems in typical locations within the various heating zones in the USA have been calculated that include a modeling of seasonal and daily temperature variations.
Two types of energy losses are compared with the electrical energy consumption for various ventilators that will be presented graphically. These energy losses will also be compared with the losses for higher quality radon mitigation systems, where the yearly energy losses are designed to be minimal. Optimization does not lead to the same results for all locations. The results will also be presented as all inclusive formulas for operational energy losses and costs including altitude corrections. The applicability of these calculations will be discussed and the case will be made that the knowledge of these issues may help an individual radon mitigation company to improve its competitiveness.

ENERGY LOSS TYPES RELEVANT TO RADON MITIGATION SYSTEMS

Operational energy costs of radon mitigation systems are either ignored or merely partially taken into account when various mitigation systems are compared. The cost that is typically recognized is (1) the direct electrical cost to operate the ventilator, but consists also of (2) conductive thermal losses and (3) convective warm and cool air losses. In the winter due to the operation of a furnace the additional operational energy costs consist of thermal conduction through the boundaries of the building (referred to later as W2), and *warm air* lost by convective replacement of warm air with cold air from outside the building (W3). In the summer, when an air conditioner or other cooling system exists, additional energy losses consist of conductive thermal losses (S2) conductions through the boundaries of the building and *cooled air* lost by convective replacement of cooled air with warm air from outside the building (S3). In calculating the total energy burden the efficiencies of equipment to effectively heat the replaced air in the winter and cool air in the summer must be included, and when operational cost rates to the occupant are calculated typical utility energy cost rates have to be included.

The direct electrical yearly energy to operate the fan (1) is easiest to measure or estimat. Measuring pressure differences across the ventilator can be accomplished directly with a digital micro-manometer that can be combined with the information from the fan curves of the manufacturer. From this information the operational volumetric flow rate can be calculated for each section of pipe. The electrical energy costs of ventilators can be approximated by its rating. Although the actual operation point for a ventilator will be below this rated power, the operational electrical energy used will be close to the maximum energy rating when large air flow rates are observed.

Conductive energy losses (W2 and S2) are hard to measure and exist in the winter as cooling of the bottom of the concrete slab by air movement caused by the system under the slab and thermal diffusion from the warm top to cold bottom of the slab (or membrane in case of a crawlspace) and vice versa in the summer. In general wooden residential buildings with floating slabs in the dryer climates are constructed with conductive losses much smaller than convective losses and it is estimated that the additional conductive losses fall within the uncertainty of the calculations of the convective losses that will follow.

Convective energy losses (W3 and S3) during heating and cooling seasons generated by a radon system, are caused by gaps and openings in concrete slabs of basements, sump pit openings, and between improperly sealed membrane-to-foundation wall boundaries, and at overlaps of membrane sections. The effect of this is not negligible and is not often included in an energy calculation.

There are two potential exceptions to radon systems causing additional convective energy losses. One exception (A) is when the additional convective air loss by the radon mitigation system from the building has the effect to reduce the loss of a fraction of air loss elsewhere from the building envelope for example by raising the zero pressure plain inside the building. This effect has been noticed in another study but

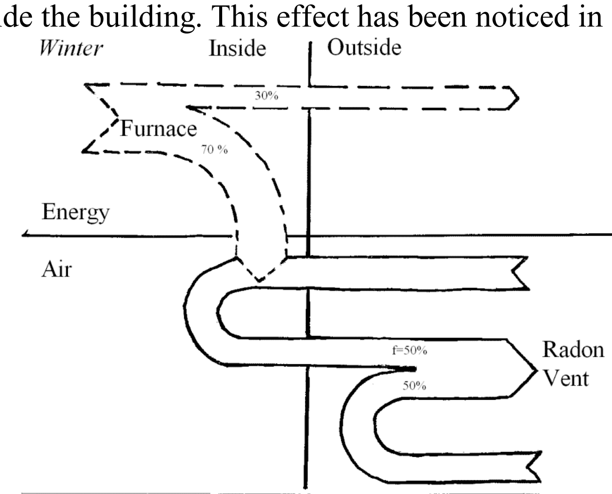

Fig. 1: Energy (dashed) and Air flow (solid) diagram for a radon system extracting warm air from the house in the winter. Energy: Top of diagram, Air flow bottom of diagram, Inside vs. outside the house is represented by the left vs right side of the diagram.

and in that study did not completely reverse the effective flow in the upstairs [1]. Another exception (B) is when a fraction of the air loss that the radon system is exhausting is unconditioned air that entered the building before it had a chance to fully mix with warm air and reach a new thermal equilibrium [2], which can be the case in a cold crawlspace. In both cases the fraction of exhausted cold air mass does not contribute to additional energy losses compared to what the building would have suffered without the radon mitigation system. In this paper we will assume that both of these cases do not apply to the situation that will be discussed. The reason for this is that in most houses with a furnace or conventional boiler or heater, by Code, one or two required make-up fresh-air openings in the basement exist preventing back drafting of the furnace, but also allowing most of the additional evacuated air by the radon mitigation system to be drawn in at this location and be mixed with the interior basement air. Thus in the generic situation the air that entered mixes fully with inside air before it is removed from the house by the radon system. However residences entirely operating on electrical appliances, or Solar or Green houses with their specific energy circumstances may have to be investigated separately.

In Figure 1 an energy-air-flow diagram is shown for a radon mitigation system in the winter. The bottom half of the diagram indicates the relevant air flow movement and top half the energy flow. In addition items in the left side of the diagram are events occurring inside the house and in the right side of the diagram outside of the house. The diagram indicates that the system draws in warm air from the inside of the building that bypasses the lowest slab of a house through its openings in the winter.

Thus the first line of defense against convective heat losses is to seal all openings from the interior of the house through and around concrete slabs to the soil with a durable caulk. The caulk has to have enough elasticity to allow for small movements of components it is adhered to without breaking, such as in the case of floating slab to foundation wall joints. Therefore special caulks are applied and insulating foams are rarely used successfully because they do not have the elastic durability,

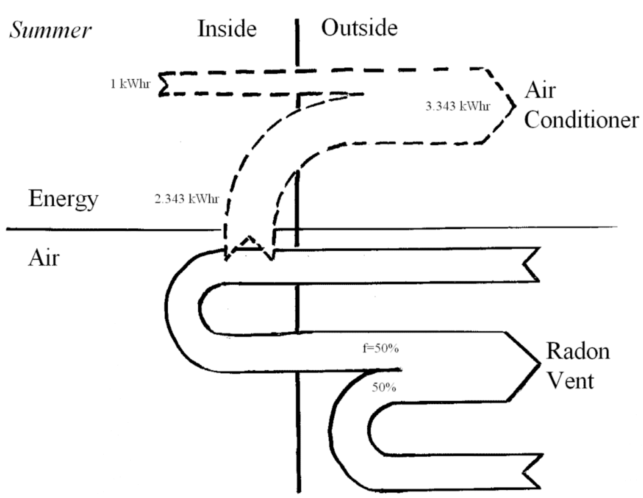

Fig. 2: Energy/Air-flow diagram for a radon mitigation system extracting cool air from the house in the summer.

resistive porosity, and adherent quality we need for radon mitigation systems.
A better sealing of these openings results in lower convective energy losses. Given the examples mentioned an effective estimate of 50% convective energy losses is a good first guess for calculation purposes in sub-slab situations with gravel as is prescribed in certain Codes.

Finally a distinction must be made between heating and cooling losses when various energy sources are being used. In these calculation we assume that in the winter a normal gas fired furnace or boiler with 70% efficiency is used and in the summer a whole house air conditioning unit is used with moderate energy efficiency whose compressor does work and uses electrical energy.

MEASURING AN AIR REMOVAL RATE FROM A BUILDING AND THE EFFECT OF SEALING THE SLAB

An unfinished basement was constructed with floating slab and gravel as sub-slab material, and an interior drain tile pipe and all openings through the slab were appropriately sealed during this research. Openings included all expansion joints near floor and walls, control joints interior to the slab in 10x10 square foot sections, whether it had cracked yet or not, to provide protection for future cracking, openings around plumbing pipes, rough-in openings, and all additional cracks visible in the slab. The existing sump pit opening was sealed with a hard cover transparent polycarbonate material to accommodate future visual inspection. Figure 3 shows the results of localized, single point, measurements of the sub-slab difference pressure across the thickness of the concrete slab material at different distances from the radon extraction cavity that were made before the sealing process was initiated. After the sealing process was completed the measurements were repeated the base pressure drop at the cavity can be roughly translated into an effective flow rate through the radon system. Using the published ventilator curves from the manufacturer of this ventilator the effective air removal rate can be estimated. In this case an effective removal rate of 280 cfm was reduced to 143 cfm just by complete sealing of the slab. This means that an effective additional air removal rate of 137 cfm is taken from this basement by the radon mitigation system with this ventilator when the basement remained unsealed compared to when the basement was sealed. This derivation was rough and ignores all other parts of the mitigation system. A more sophisticated analysis [3] taking the friction of the equivalent length of the piping in this 1-branch system into account allowed a modeling of the proper sub-slab cavity pressures resulting in flow rates of 167 cfm and 97.8 cfm The resulting cavity resistance change that was used to model this was 6.65 10^{-6} min/cf and 3.65 10^{-5} min/cf. This demonstrates what size changes of cavity resistance can be accomplished by sealing alone. The total effective flow rate change was 69.2 cfm.
This type of data should have a consequence for new home construction design. If RRNC building techniques require gravel (or gravel is chosen) and these systems do not require sealing of the slab at the same time, or sealing is not properly inspected by the municipal inspector, basements have been observed to be finished immediately during construction or later without appropriate sealing of the slab, despite new home building

Codes that require it. This will have the consequence that the building occupant will be burdened with additional indoor air losses of a similar magnitude as we just presented when radon systems are installed while proper sealing is no longer possible because openings and gaps are not reachable any more. Moreover, expansion joints of 40 year old homes have been observed to have been completely deteriorated, which will affect the operation of currently installed radon systems well into the future when such joints could not be sealed during installation. Techniques to seal expansion joints of finished basements are either very costly (remove drywall and plates to reach the joints) or messy (clean, vacuum and caulk the joint through the drywall) and satisfactory methods are not existing at this moment, but will be needed in the future when advanced diagnostic methods will show which houses have unacceptably high energy losses for the occupants living in them in the future. This is a current challenge for the radon industry to solve.

This paper will address the question what magnitude of energy losses and costs can be expected in these situations. If control grooves in slabs are not caulked, or are sealed with the wrong caulk material that tends to harden too much and crack later, or grooves are not properly cleaned and vacuumed before caulking and caulk has been observed to peal loose with time, a significant additional operational air removal loss can be introduced by activation of passive radon removal systems, even when they are

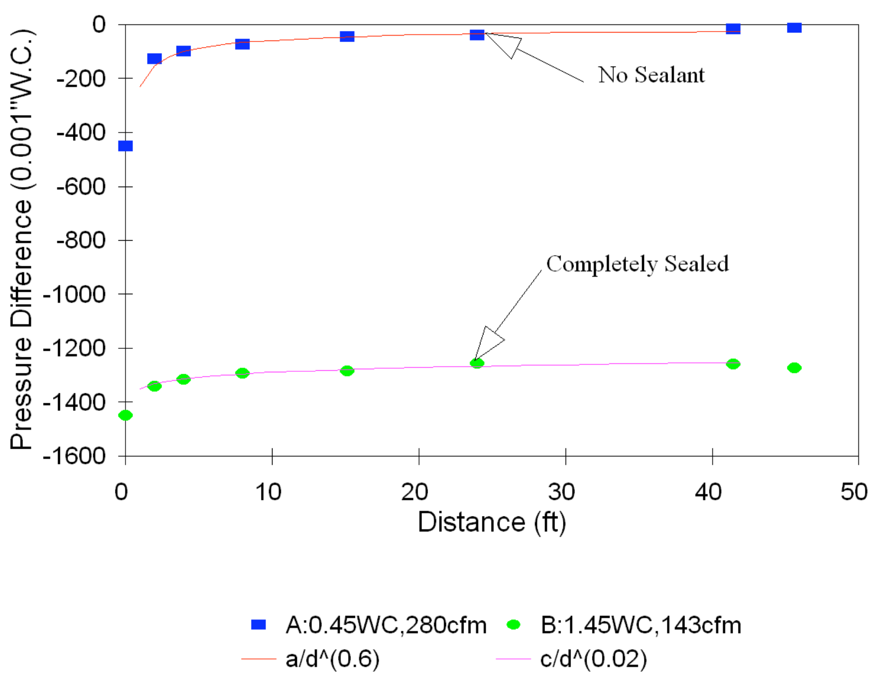

Fig. 3: Effect of sealing an unfinished basement on the radon pressures and system air removal flow from the building with large gravel and interior perimeter drain under slab. The reduction in air removal rates based on complete simulation of the system [1] shows that in this case a removal rate of 69.2 cfm air is prevented from the building, when complete sealing is applied before finishing the basement (Ventilator power is 150 W).

activated much later. An obvious advantage is that once the floor is sealed a ventilator with smaller power can be chosen to mitigate the same building, reducing air losses even further as well as reducing direct electrical costs and Air Conditional losses in the summer. As an additional benefit this causes a lower noise burden on the living area.

If in the example of figure 3 all of the remaining air flow through the radon mitigation system came from the sub-slab material under the building that ultimately came from the surrounding outside soil a reduced energy loss for this radon removal system would have been introduced. As a second example we show in Figure 4 a similar situation with pea-size gravel and no interior perimeter drain. It can be seen that the sub-slab resistance for air flow is reduced and is not symmetric around the cavity because of the two data points near 27 ft distance that have quite different values. When sand and clay are used the heating losses are reduced even more because of the low porosity of the material; however when low resistance channels exist in the sub-slab materials cracks and expansion joints can be reached and can provide significant pathways with higher flow with similar concern for operational energy and cost losses for the system.

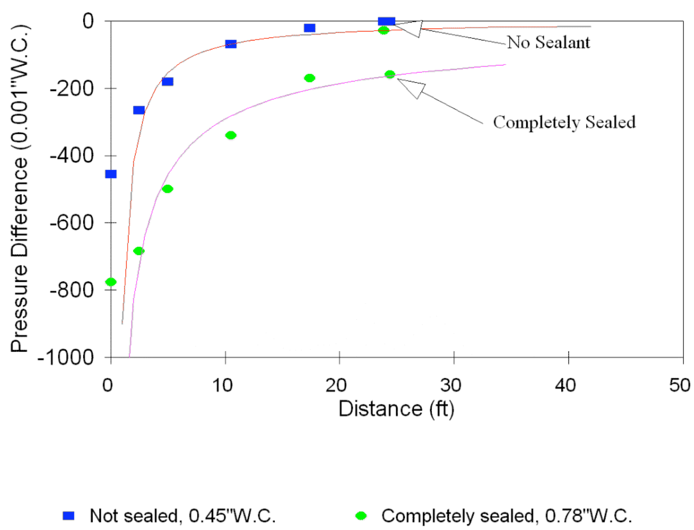

Fig. 4: Effect of sealing an unfinished basement on the radon pressures and system air removal flow from the building with sand and pea gravel under the slab and with no interior perimeter drain. The reduction in air removal rates based on the complete systems analysis shows that in this case a removal rate of 28.2 cfm air is prevented from the building, when complete sealing is applied before finishing the basement (Ventilator rating is 83 W).

RADON REMOVAL EFFECTIVENESS IN VERY LOW ENERGY LOSS SYSTEMS

The two examples presented before indicate the importance of proper sealing when leaky slabs are encountered. Although improvements can be made in existing homes there is no substitute for being able to work the problem from the ground up. In the example we will look at in this section a Radon Risk Evaluation had been performed on a location where the house was going to be constructed. The basement had been excavated and the concrete foundation walls poured. The Radon Risk Evaluation indicated that the finished house would have had a radon concentration of approximately 150 pCi/L (See Fig. 5). We were asked to install our most effective and energy efficient radon mitigation system that the owners preferably would like to see work as a passive system, to avoid any noises added to the house and surroundings. A double barrier passive system was installed that resulted after completion in a measured radon concentration (2 day short term test, closed house conditions) of approximately 25 pCi/L. During this time the plumber had left an 8 inch slit in the crawlspace membrane near the water heater. After repair and activation of the membrane very low levels were reached. A follow up measurement operating the system as a passive system measured a level of 5.2 pCi/L.

Additional measurements with a Continuous Radon Monitor (femtotech CRM 510) were done by operating various fans and electronically operating fans at various

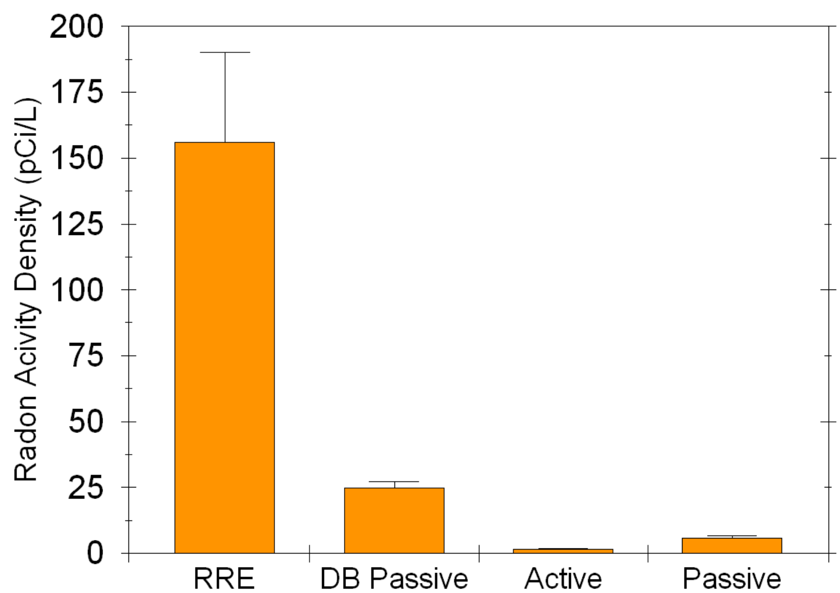

Fig. 5: Radon Risk Evaluation and double barrier passive and active operation of high energy efficient combined ASD and membrane radon mitigation system.

rotational speed. Pressures across the fan were measured whose flow rates had been compared with measurements in a bench set up elsewhere. From figure 5 it can be seen that the measured radon levels at different flow rates had a background. A theoretical fit based on a volume theory resulting in a hyperbolic shape showed a fit as shown that indicated a background of 0.85 pCi/L. This background was reached for an extra

powerful fan operating at its full power at 150 Watt which with the low frictions in this two-branch mitigation system was at flow rates of 150 cfm.
Similarly we found that even at very small flow rates the radon level did not rise above 2 pCi/L even at a flow rate of as little as 20 cfm. The ventilator used was a 12 V-DC fan drawing a power of 3.2 Watt. The physical dimensions of the ventilator was a 2 inches diameter axial fan that was inserted inside the 4-inch PVC pipe on a perpendicular polycarbonate holder that allowed leakage for water around it through the pipe.

From this graph we can conclude that with limited testing not much benefit seems to be indicated to run a 150 cfm 150 Watt commercial radon ventilator compared to a 3.2 Watt ventilator. However it must be kept in mind that the membrane system was hermetically double-sealed below the slab and a full interior perimeter drainpipe was inserted in the gravel under the double membrane, which treatment can only be done during new home construction.
Thus the question is if it is possible to reduce energy losses through sealing and reducing the power of the ventilator while maintaining a high radon removal efficiency. A theoretical fit curve of the data indicates that to minimize the radon concentration a maximum power of the ventilator would be required. The theoretical fit shows a

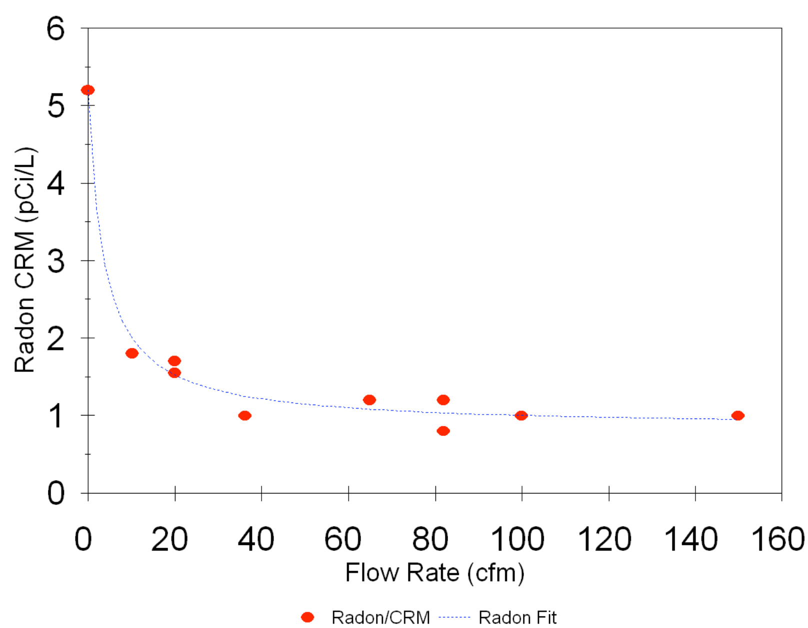

Fig 6 Short term radon tests in the house after installation of a high energy efficient radon mitigation system allowing a number of ventilators to run at different power. Ventilator powers range from 3.2 W (20 cfm) to 150 W (150 cfm).

background of 0.85 pCi/L that is not affected by the flow rate. Its interpretation is that this background is caused by a combination of radon in the outside air around the building and the combined sources of building materials inside the building.
The choice of maximum air flow through the system would add unnecessary energy losses and additional noise to the house to the extent that a homeowner may not want to

live with. This is an example in support of the fact that the requirement in the author's opinion for a 'higher quality' radon mitigation system is not to uniquely 'maximize' the radon reduction, but to 'optimize' a number of variables. The four desired variables to optimize simultaneously are (1) maximizing radon removal, (2) minimizing energy losses, (3) minimizing the noise burden on the most sensitive living areas, and (4) minimizing visibility of the system. The latter is added such as not to affect curb appeal and visibility from a backyard and low visibility through the most frequently visited areas in a house. Systems installed in this way will be functional and avoid adding a burden to the house. When done well in new home construction by conscientious mitigators passive mitigation systems can be designed optimally in this sense and provide for an uncomplicated activation, if radon tests show the need later.

A MODEL FOR EXTERIOR TEMPERATURES

In order to calculate which energy losses a radon mitigation system adds to the utility costs of an occupied residence we must first define the baseline, which is the outside environment with which the house exchanges air.

In the industry and academics a useful measure in terms of heating and cooling degree days has been used for decades [4]. Limitations of the method are that it only takes into account temperatures due to space heating, not when solar heating becomes important. In this Sense the CDD has limitations. It assumes the Heat Loss is proportional to the temperature difference. In most cases cooling is applied only in a few rooms which limits

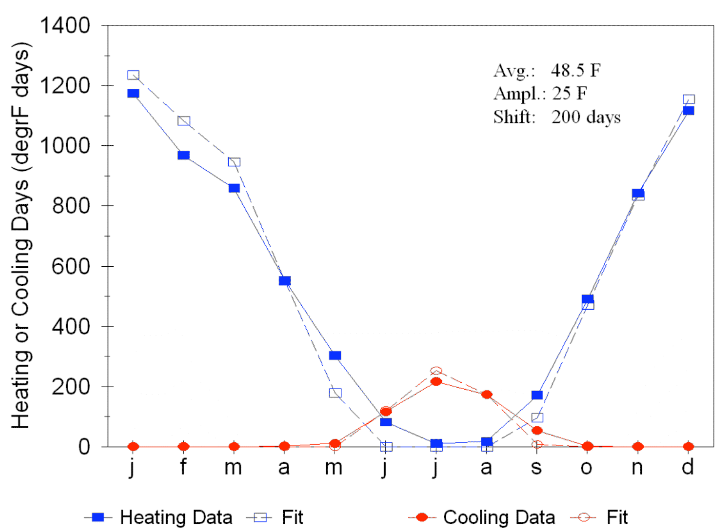

Fig. 7: Example of a match of a three parameter model that fits the seasonal cycle of temperatures for thirty year average monthly Heating Degree Days and Cooling Degree Days for Fort Collins CO. February's shorter month causes a seeming irregularity.

the usefulness of the method. [5]

A single heating degree day based on the reference temperature 65 degrees Fahrenheit is defined by the average temperature during one day to be 1 degree Fahrenheit below 65 degrees, relating to the assumption that the occupant would want to heat the residence during that day by an average of 1 degree to bring it from 64 to 65 ^{o}F. Five different Climate Zones are classified for the HVAC industry in which specific recommendations for use and operation of furnaces and air conditions may vary across the Climate Zones.

Based on the information of thirty year averages of heating degree days (1971-2001) [6] and cooling degree days (1961-1990) [7] a model for exterior temperatures can be made with an average amplitude describing the seasonal temperature cycle, and a number of days shift from January 1, can be made that approximates best the temperature for each day during the year. The consistency of this three parameter fit with the heating degree days curve as well as the cooling degree curve is shown in figure 7. The curve can be captured remarkably well with these three parameters.

On top of this seasonal cycle a daily cycle is chosen with a temperature amplitude based on average high-low temperature differences within the day. The resulting model can be considered a reasonable approximation of the average hourly temperatures that we can give with a total of only four parameters.

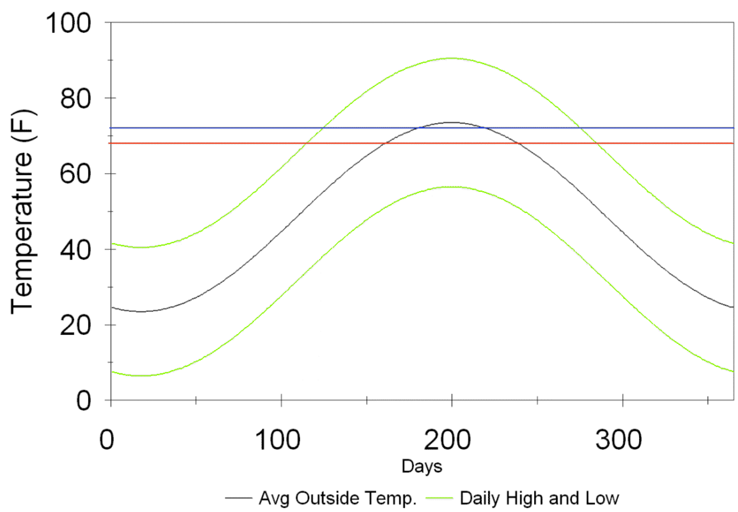

Fig. 8 Hourly modeling of outside temperatures in Fort Collins CO where the daily highs and lows are taken 17 ^{o}F up and down from the average temperature (black line). Heating of the house is set at the point where the outside temperature is below 68 F (red line) and cooling starts when the outside temperature is above 72 ^{o}F (blue line).

The daily modeling parameters for outside temperatures in Fort Collins, CO, throughout the year are exemplified in figure 8. The outside temperatures vary between the two extremal green curves with black curve being the daily average The red horizontal line in this figure indicates the outside temperature 68 ^{o}F below which heating

Table 1 Locations across various Climate Zones with Fit parameters to the 30 year averaged HDD and CDD data

City	Index	State	Climate Zone	HDD	CDD	Temperature (°F)	Seasonal variation (°F)	Shift (days)	Daily Ampl. (°F)
KEY WEST	KW	FL	5	64	4798	87	7	210	5
SAN DIEGO	SD	CA	4	1063	984	64.7	7.8	216	10
CHARLSTON AP	Charl.	SC	5	1973	2266	66	17	199	17
ATLANTA	Atl	GA	4	2827	1667	62	18	200	17
NASHVILLE	Na	TN	4	3658	1616	59	21	202	17
NEW YORK C.PARK	NY	NY	3	4744	1096	55	22	204	17
INDIANAPOLIS	Ind.	IN	2	5521	1014	52	23	200	17
FORT COLLINS	FC	CO	2	6587	571	48.5	25	200	17
SIOUX FALLS	SiFa	SD	1	7746	744	44	27	197	17
SAINT CLOUD	SntCl	MN	1	8812	417	43	30	200	17
CARIBOU	Car	ME	1	9505	131	39	28	201	17
ANCHORAGE	An	AK	1	10470	0	36	22	194	17
DILLON	Dil	CO	1	11208	0	35	21	206	17

of the inside air in the house is chosen. The blue horizontal line gives the temperature 72 °F above which cooling of the inside air in the house is chosen.
The Climate Zones follow the classification for heating zones. HDD is an abbreviation of Heating Degree Days and CDD for Cooling Degree Days which are often chosen with a reference temperature of 65 °F. Classification boundaries are shown in Table 2. Temperature, Seasonal Variation, in degrees Fahrenheit, and Shift in number of days with respect to January 1, are the best three parameter fit that was found to simulate both HDD and CDD based on their 12 monthly average recorded values over several decades at each City's location. Daily amplitude is a reasonable guess based on location, with locations near coasts and equator assumed to have smaller daily variations than all other locations.

Table 2: The definition of Climate Zones in Cooling Degree Days and Heating Degree Days with a reference temperature of 65 °F is used in the heating and cooling industry. Locations in all zones are represented in our calculations, see Table 1.

1	Fewer than 2,000 CDD and more than 7,000 HDD
2	Fewer than 2,000 CDD between 5,500 to 7,000 HDD
3	Fewer than 2,000 CDD and between 4,000 to 5,499 HDD
4	Fewer than 2,000 CDD and fewer than 4,000 HDD
5	between 2,000 CDD and 4,000 CDD

NUMERICAL CALCULATIONS OF OPERATIONAL COSTS

The outside temperature simulations at each location are used in an hour by hour method to numerically calculate the convective heating and cooling losses:

$$\delta Q_{perhour} = C_{p,m} n \Delta T \qquad (1)$$

The heating energy needed is expressed in Joule and $C_{p,m}$ is the molar heat capacity of air at constant pressure, n is the number of molecules measured in moles of air (Avogadro: 6.022 10^{23}molecules/mol) and ΔT is the temperature difference in Kelvin we need to accomplish in heating or cooling the gas. The molar heat capacity, $C_{p,m}$ at constant pressure for a diatomic ideal gas, which is appropriate for heating dry air at atmospheric pressure, can be expressed in R_u, the universal gas constant, whose numerical constant is 8.314 Joule/mol K, as follows:

$$C_{p,m} = \frac{7}{2} R_u = 29.085 \text{ J/(Mol K)} \qquad (2)$$

which can be converted in values we will recognize in other formulas later. The heat capacity at constant pressure can be converted to a volumetric quantity:

$$C_{p,m} = 5.6815\ 10^{-6} \text{ kWhr/(ft}^3\ {}^o\text{F)} \qquad (3)$$

$$= 0.019375 \text{ Btu/(ft}^3\ {}^o\text{F)}$$

The later value is well known in the heating industry as approximately 0.02 Btu/(ft^3 ^{o}F). Using the ideal gas law, PV=nR_uT the heat added to an air mass of n mole in volume V that is drawn into the house and that is increased by temperature ΔT can be written as:

$$\delta Q_{perhour} = C_{p,m} n \Delta \mathrm{T} = \frac{7}{2}\left(\frac{PV}{T}\right)\Delta T \qquad (4)$$

This means that a volume of cold air drawn to the inside, V, every hour is the product of a fractional loss, f, and the volumetric rate R moved by the ventilator through any cross section of the main radon vent pipe, which when expressed in cubic feet per minute (cfm) must be multiplied with 60 to calculate the air volume per hour and with 0.3048^3=0.02831687, which is the volume of 1 cubic foot expressed in m^3.

The temperature difference as calculated per hour and converted from degrees Fahrenheit, t, to absolute units in Kelvin, T, can be written as

$$\Delta T = \frac{5}{9}\left[t_i - \left(t_o - t_A \cos(2\pi \frac{t}{24})\right)\right] \qquad (5)$$

The average temperature T at which the energy is heated, in equation 4, is taken to be the freezing point of water, which is 273 Kelvin, and is a good approximation for the average temperature of the air when winter air is heated, introducing only a small error. The outside daily average temperature in degrees Fahrenheit is simulated by:

$$t_o = t_{Avg} + t_{SeasonalA} \cos(2\pi \frac{t}{24}) \qquad (6)$$

Converting the expressed energy from Joule to kWhr requires a factor 2.78 10^{-7} kWhr/J. The energy efficiency of the method to generate a unit of air volume must be included by dividing through the efficiency of the device that we choose to use.

For a gas fired furnace the efficiency, g, will be taken here to be 70%, as was also indicated in figure 1.

Thus putting all factors together we can calculate the heating energy needed per hour expressed in kWhr per hour, by writing equation 4 as:

$$\delta Q_{perhour} = \frac{7}{2}\left(P\frac{60\times 0.028317\times fR}{273}\right)\left[\frac{5}{9}\left(t_i-(t_0-t_A\cos(2\pi\frac{t}{24}))\right)\right]\frac{2.78\cdot 10^{-7}}{0.70} \qquad (7)$$

Using the value for 1 atmosphere, P=101,325 Pa, and by combining the constant factors we find for the energy loss in kWhr per hour by a simple rearrangement of the factors:

$$\delta Q_{perhour} = \frac{60\times 5.681\cdot 10^{-6}}{0.70} fR(t_i-(t_0-t_A\cos(2\pi\frac{t}{24}))) \qquad (8)$$

where the efficiency 0.70 shall be replaced by the Coefficient of Performance when we will be considering cooling of air instead of heating later.

The hourly energy rate loss could be easily analytically integrated if this formula was valid during the entire year but this would not be realistic. To simulate the behavior that is closer to reality we use a criterion that switches the furnace on and off depending on the outside temperature condition. In these calculations we use the criterion that for all outside temperatures below the t_i=68 ^{o}F the furnace will maintain the house to this target interior temperature by heating the air that is drawn in from the outside. Similarly for all values above 72 ^{o}F in the summer our simulation describes to cool the outside air with an electrical air conditioner. In case we are cooling outside air entering the house in the summer we will replace the furnace efficiency 0.70 by the Coefficient of Performance. The Coefficient of Performance is dimensionless and indicates how much heat energy (in any unit) can be removed from the cold reservoir of the air conditioner per unit energy work done by the unit. This was also indicated in figure 2.
A typical air conditioner used these days in homes (not the newer high efficient type) with an energy efficiency rating (EER) of 8 Btu/Whr will have a Coefficient of Performance (COP) of 2.343. This is the value we will be using in this paper yet it can be easily adapted if a different COP is known in the final presentation of the results.

In Figure 9 we have displayed the daily energy losses due to the operation of a radon mitigation system calculated based on the hourly modeling of exterior temperatures in Fort Collins. The horizontal scale starts on January 1. This simulation shows that for this location the energy losses predominantly are from the heating, next the electric loss form running the ventilator and the energy losses through cooling are smallest.

The energy losses are converted to dollar costs based on the cost rate for the utility applicable i.e. Natural Gas cost rate for low outside temperatures during heating periods, and Electrical cost rate for air conditioning cooling when outside temperatures are too warm. The current cost Rates for energy sources are given in the table 3, and were calculated from the billings of local energy providers for 2009: Future estimated

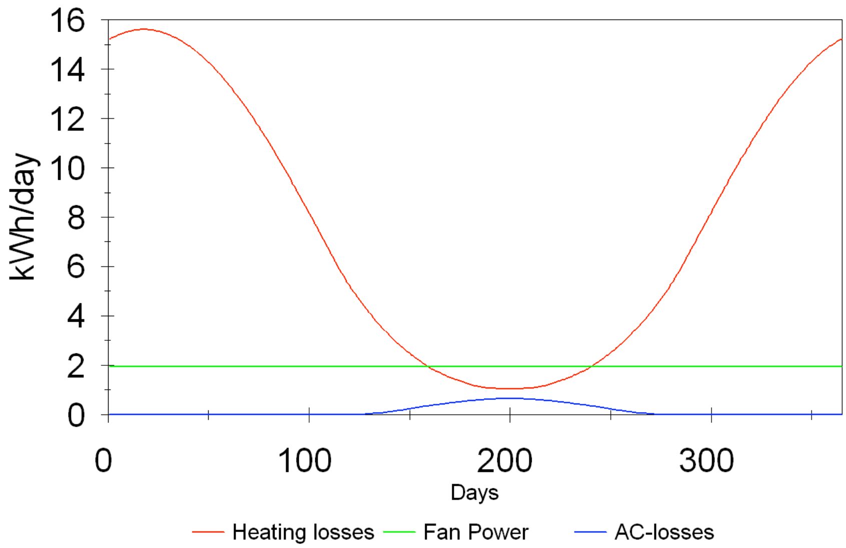

Fig 9.: Energy losses due to operation of a radon mitigation systems calculated based on the hourly modeling of exterior temperatures indicated in Fig. 7 for Fort Collins, CO (Ventilator: 150 W ventilator, 120 cfm,, Internal losses: 60 cfm).

rates are including expected rate increases within the next decade. It should be clear that depending on location and cost rates the ranking of importance of the three components in Figure 8 for the occupant in dollars spent may vary.

Using these Energy cost rates and the previously discussed convective loss efficiency of 50% (LE=0.5) and Furnace or boiler efficiency of 70% (FE=0.7) and for the AC unit an EER of 8 Btu/Whr (COP of 2.343) we can calculate the operational costs per year for various ventilator configurations and locations.

Table 3: Local utility energy rates in 2009 in comparison to future expected rates that were used in these calculations

Energy source	Local Current Energy Cost Rate (2009)	Future Estimated Energy Cost Rate
Natural Gas	3.0 c/kWhr	4.0 c/kWhr
Electricity	7.8 c/kWhr	12.0 c/kWhr

A large variation of operational costs was found with location. Total radon mitigation operational costs were found to vary from less than $225 per year at the warmest regions to $500 per year in the coldest regions considered for the largest air-losses considered in the calculations and using heating by gas. The largest contributor to operational costs was generally the heating cost, except for the warmest regions.

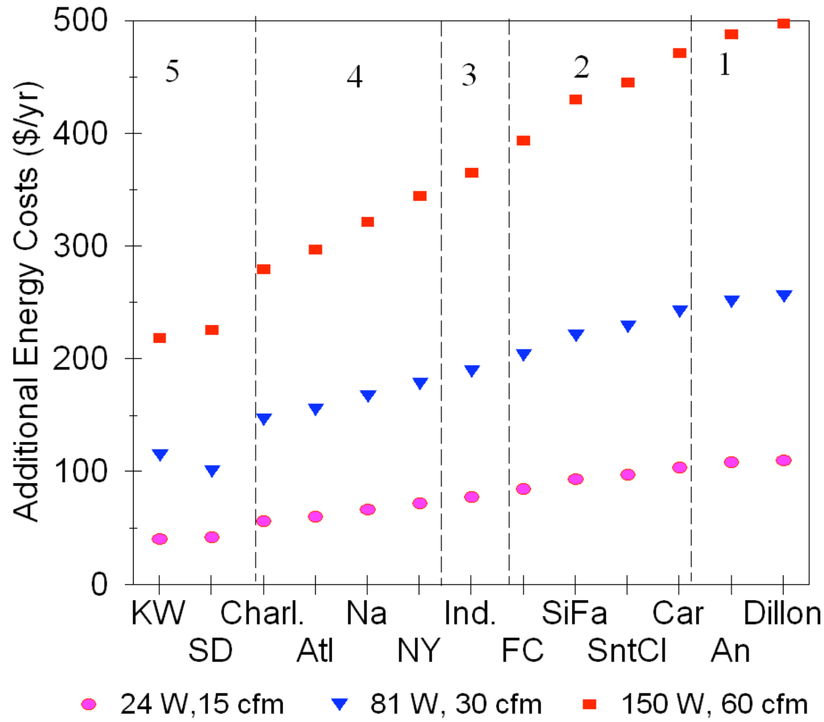

Figure 10: Additional Energy Cost calculated by using hourly computer model following parameters and abbreviations defined in Table 1 and the future estimated energy rates from table 2.

THE BEST FIT FORMULA ACROSS LOCATIONS AND SYSTEMS

In general the three most significant contributions to the energy losses are the electrical power operating the fan continuously and the two convective losses causing outside air to be heated in winter and cooled in summer. Rather than the detailed derivation from first principles shown in the previous section we will look here to start the description from the point of view of proportionalities that can be expected on reasonably grounds and using the numerical data we calculated in the previous section we will try to obtain effective proportionality constants for the largest range of realistic parameters. When this is accomplished and the range of variables for which the simplified formula is a good approximation this formula can be used within its validity ranges to calculate additional results with a reasonable degree of accuracy, without having to resort to additional numerical calculations. However it must be kept in mind that there is no guaranty this formula will be describing all data points correctly with a single set of effective parameters. On the other hand if we wanted to we could have derived a single set of exact parameters for each individual location.

Since the ventilator operates throughout the year the energy loss over the year is proportional to the power, *P*, with a proportionality constant, *a*:

$$\alpha = aP \qquad (9)$$

If we draw a fractional volume rate of air, *f*, from the interior of the house and the rest from the soil under the house, given a certain air removal rate by the ventilator, *R*, the energy loss due to heating or cooling will on the average be linear with the rate at which the air is removed from the interior, *fR*. When heating of the air is needed the energy loss rate is approximated to be proportional to the number of heating degree days for any given location, *H,* and inverse proportional to the efficiency, g, with which this heating occurs.
Furthermore the heating energy will be proportional to the mass in the air at a certain volumetric rate that is replaced, thus it will be proportionally to the density of the air at the altitude where the house is located, which is proportional to the barometric altitude formula. This can be described as an exponential factor, where in a good approximation the pressure drops a factor 2 due to an altitude increase of 5.5 km, for which the parameter L will be used. Defining a proportionality constant, *b*, that will be interpreted later, leads to the simple relationship for all excess connecting heating energy loss due to an operating ASD radon mitigation system in units of energy:

$$\beta = b\frac{HfR}{g}2^{-\frac{A}{L}} \qquad (10)$$

Similarly, the excess convection cooling energy loss is approximated to be proportional to the number of cooling degree days for any given location, C, and inverse proportional to the efficiency, e, with which this cooling is accomplished by the Air Conditioning unit. Defining an effective proportionality constant, c, that will be interpreted later, leads to the simple relationship for all heating losses in units of energy:

$$\gamma = c\frac{CfR}{e}2^{-\frac{A}{L}} \qquad (11)$$

Thus the total energy loss to the occupant of the house due to the radon mitigation system per year can be described by adding the three contributions:

$$\mathrm{E} = aP + (b\frac{H}{g} + c\frac{C}{e})fR2^{-\frac{A}{L}} \qquad (12)$$

The energy make-up efficiency in terms of heating of the air was included in the simulations, thus the proportionality constant, *b,* does not include the efficiency factor for a natural gas furnace (g=0.70), indicating how much energy of the source energy it takes to produce a unit energy of heated air. For example when an electric heating element would be used this parameter would be 100% (g=1.0).

When using the air conditioner, the efficiency is equal to that of a reversed heat pump with efficiency larger than 1. For an air conditioner with an Energy efficiency Ratio (EER) equal to 8, the coefficient of performance (COP) is 2.343, which means that for every Joule electrical energy used by the air conditioner 2.343 kWhr of heat is transported from the interior of the building to the outside.

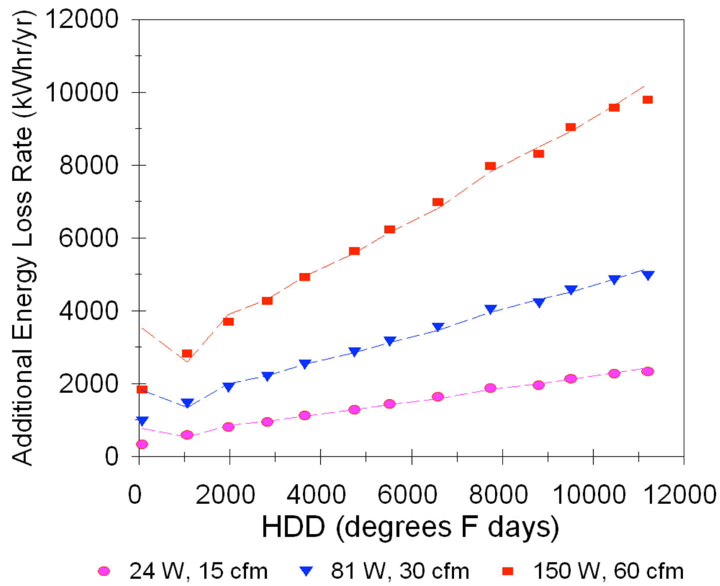

Figure 11: Best fit for largest group of data by adjusting the defined effective proportionality constants. Key West and to a lesser degree Dillon are the only significant deviations when these effective values of the parameters are used.

The electrical cost of operating the ventilator can now be calculated by multiplying the first factor containing the power directly with the electrical energy cost rate factor, *ε*. The cost rate factor for the heating energy loss term is given by the energy cost rate of the source energy,γ, which although it differs in case natural gas, electric, oil or propane are used, can be accounted for easily using the formula.

In addition to the Future estimated energy cost rates shown in table 3 we have chosen the following set of parameters in the formulas consistent with our earlier numerical calculations:

$$\varepsilon = \$\ 0.12\ /\text{kWhr}$$
$$\gamma = \$0.04\ /\text{kWhr}$$
$$g = 0.70$$
$$e = 2.343$$
$$A = 0\ \text{ft}$$

The only parameter that is not realistic in many locations is the altitude, A, which is chosen to be the value at sea level for all locations (1 atmosphere= 101,325 Pa). This is done since the pressure in the numerical simulations we compare with in equation 7 is also taken tot be 101,325 Pa. We will comment on altitude effects later.

The complete formula for the operational cost to the home owner or occupant of operating a radon mitigation system with using natural gas to heat the house is thus:

$$\begin{aligned} U &= a\varepsilon P + (b\gamma \frac{H}{g} + c\varepsilon \frac{C}{e}) fR2^{-\frac{A}{L}} \\ &= uP + (vHfR + wCfR)2^{-\frac{A}{L}} \end{aligned} \qquad (13)$$

All quantities are known except for the proportionality constants, a, b and c. The proportionality constant a can exactly be calculated because the ventilator is running all the time throughout the year. By expressing the utilities rate costs, U, in $/yr and the power P in Watts, the proportionality constant is simply the number of 1000 hours in a year (khr/yr). This number is 8.759.

Since both *b* and *c* are effective parameters, their value can be determined by fitting the theoretical behavior to the simulated numerical data.
The proportionality constant b is the costs in dollars per year for a unit of air. This method on the simulated data leads to the following best fit values excluding for Key West and Breckenridge, the extremal data points.

Energy parameters	Fit Values		Units
a	8.759		(kWhr/yr)/W=k hr/yr
b	0.009283		kWhr/(HDD cfm yr)
c	0.01760		kWhr/(CDD cfm yr)
Cost parameters	Future	Current	
u	1.051	0.6831	($/(W yr)
v (for natural gas)	0.0005380	0.0004035	$/(HDD cfm yr)
w	0.0004570	0.0002971	$/(CDD cfm yr)

Table 3: Effective parameters that fit data well, except for Key West.

The energy costs across Zones for various air removal rates at the projected source energy rates are given as data points in the following figure:

The parameters *b, c, v, w* can be reinterpreted by writing them in terms of the heat capacity of air at constant pressure at 1 atmosphere pressure, as was introduced in equation (3) in kWhr/ft^3 ^{o}F. This can be done by factoring out a few trivial factors. Because we are converting the quantity from unit cfm which has the time unit minute in it to HDD which has the unit day in it, the number of minutes in a day has to be factored out and we the result are written in terms of effective, dimensionless *f*-parameters.
For the energy parameters this is:

$$b = f_b \cdot 24 \times 60 \times 5.6815 \cdot 10^{-6} \text{ kWhr /(HDD cfm yr)}$$

$$c = f_c \cdot 24 \times 60 \times 5.6815 \cdot 10^{-6} \text{ kWhr /(CDD cfm yr)}$$

Similarly, for the operation cost parameters, it makes sense to factor out the cost rate and efficiency of the utilities energy conversion:

$$v = f_v \cdot 24 \times 60 \times 5.6815 \cdot 10^{-6} \cdot 0.04 / 0.7$$

$$w = f_w \cdot 24 \times 60 \times 5.6815 \cdot 10^{-6} \cdot 0.12 / 2.343$$

The resulting dimensionless *f*-parameters introduced in these equations are the various effective proportionalities close to unity. The following are the best result using the linear least square fitting method:

Table 4: Least square fitted, best values of the dimensionless fit parameters that describe the numerical operational heating and cooling energy losses and costs.

f_b	1.134
f_c	2.15
f_v	1.15
f_w	1.09

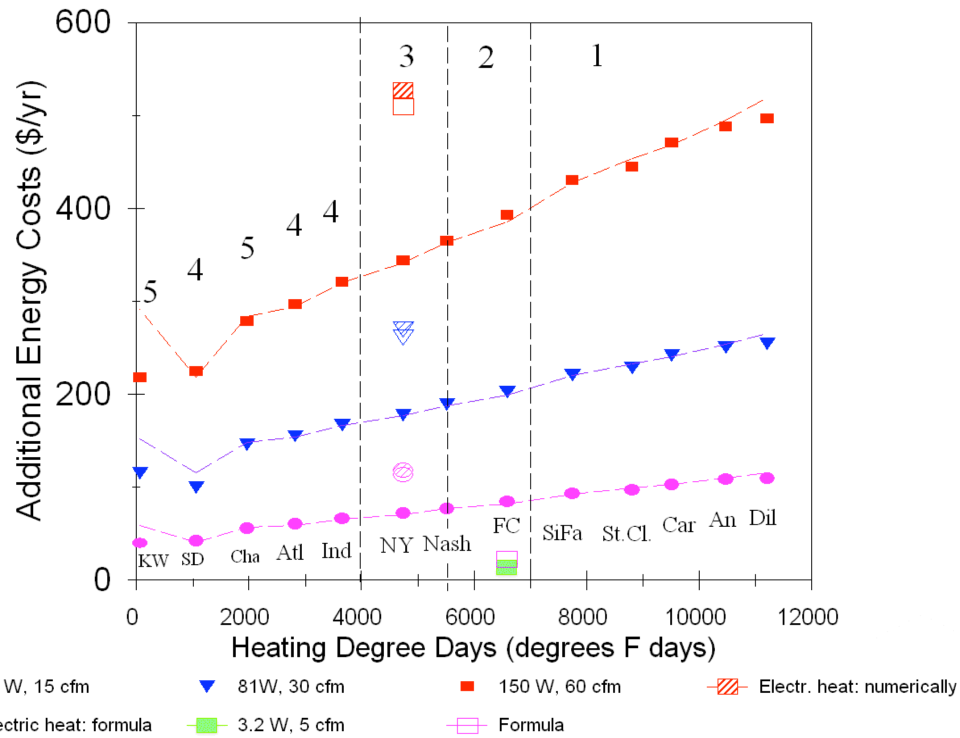

Figure 12.: Energy Cost formula compared to numerical simulation for various ventilator of various strengths and simulated air vent losses fans and scenarios. In addition to the data introduced in Fig. 10, three data points for New York were calculated for electric heat and the low power fan in Fort Collins.

These are displayed as dashed lines in the figures 11 for energy losses and 12 for energy costs. There are two reasons why the *f*-parameters are different from unity. This is because (1) the exterior temperature model takes into account daily variations, and (2) the switch-on temperatures of heating and cooling equipment was taken at 68 °F and 72 °F, respectively, which is different from he 65 °F for which the HDD and CDD values can be found in each location. Thus comparing with the HDD and CDD with reference base 65 °F at any location, we are working with somewhat misalligned variables. However this problem is taken care of by introduction of these *f*-parameters following from a least square fit across most of the HDD range..

A few additional data points are shown in Figure 12 both as numerically evaluated and using the formula, in order to see how accurate the formula works for a variety of situations. The three dashed data points were calculated by the simulation method for each of the three ventilator loss situations in New York and shifts are indicated to higher costs. In addition one data point for Fort Collins with the lowest energy fan introduced in chapter 3 is also shown in this Figure. Its' volumetric rate was 20 cfm, but because of the special sealing applied, we estimate it to take no more than 5 cfm from the house. The energy efficiency of this system as a whole is shown to be impressively low compared to any other data point in the Figure.
The formula was next applied for all data points and it can be seen that a good approximation of the formula to the three data points was obtained for electric heat. This shows reliability of the formula in predicting a variety of circumstances. The solid numerical data points are identical to the previous figure.

ENERGY LOSSES RELATIVE TO ELECTRICAL COSTS

In Figure 13 it is interesting to compare the ratio between heating and electrical

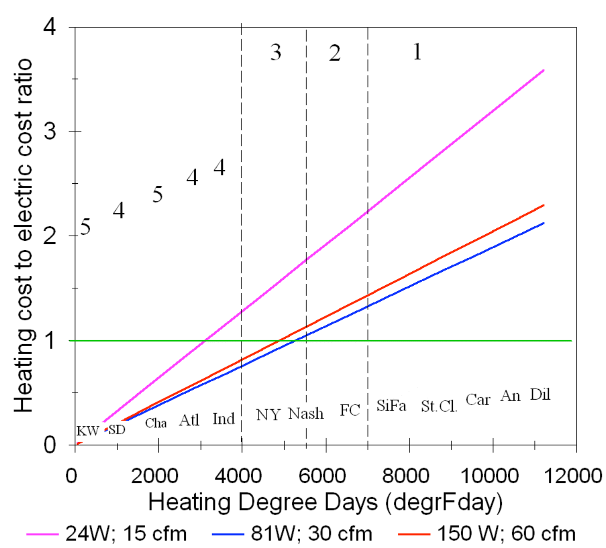

Fig.13: The ratio of heating and electrical Costs across the HDD values.

cost to run the ventilator for each of the three considered mitigation scenarios:

$$R_h = \frac{C_h}{C_e} = \frac{b\gamma HfR}{a\varepsilon gP} \qquad (14)$$

In general cooling contributes less than the electrical costs as shown in figure 14 and in zones 1,2 and 3 less than 40% of the electrical costs. In Caribou we see a value over 50%. Only in Key West we calculate a fraction above 60% of the electrical costs which has to be ignored due to its known inaccuracy of these parameters for Key West.

$$R_c = \frac{C_c}{C_e} = \frac{cCfR}{aeP} \qquad (15)$$

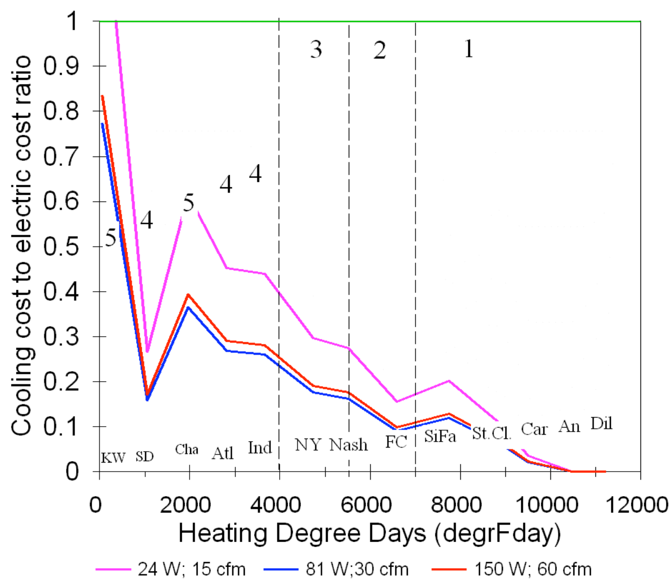

Fig.14 The ratio of cooling and electrical costs across the explored HDD range

Whereas heating contributes to most of the costs. For heating zones 4 and 5 with values under 2000 HDD the cooling can contribute equal or more than heating.

In terms of the yearly total energy costs relative to the yearly electrical costs as shown in figure 15 for the midrange and more powerful ventilator considered we calculated a factor of 3 for Dillon, Colorado, but the moderate zones 2 and 3, this factor is calculated to be twice the electrical costs.. For the warmest regions, heating Zones 4 and 5 the total energy costs to electrical cost ratio is calculated to be generally smaller than a factor

2.5. The least powerful ventilator had the highest factors across the entire HDD range which were up to a factor 4.5 in the coolest climate of Zone 1.

$$R_{tot} = 1 + R_h + R_c \qquad (16)$$

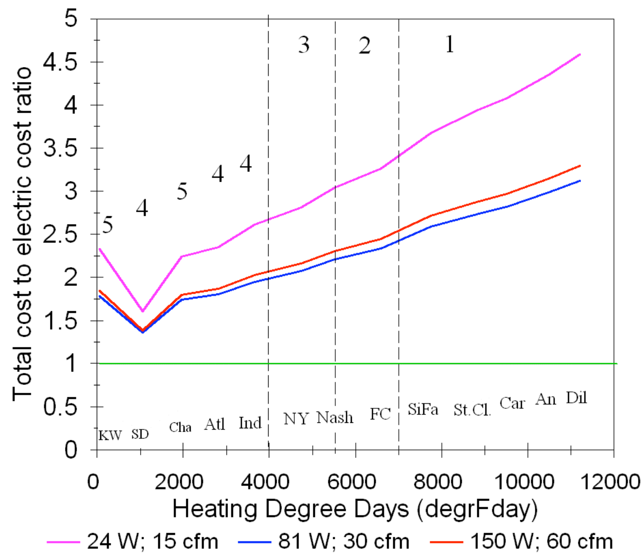

Fig.15 The ratio of Total energy costs calculated and electrical Costs across the HDD values

THE EFFECT OF ALTITUDE

The effect of altitude on convective energy losses is directly related to the pressure at which the volume of air is extracted by the mitigation system from the house. The barometric altitude formula describes the pressure loss as a function of altitude due to a layer of air carrying all air above it while the layer itself is carried by all air below within the constant gravitational field of the earth. The exponentially decreasing formula with increasing altitude that results is known as the barometric altitude formula and can be written as:

$$P(z) = P_0 e^{-\beta z} = P_0 \cdot 2^{-\frac{z}{L}} \qquad (17)$$

with β a known constant and P_0 equal to 1 atmosphere at Sea level (at z=0 ft). The value of β allows us to write this formula alternatively as indicated with L approximately 5.5 km, the altitude increase where the pressure assumes half its value.
As an example figure 16 indicates the relative change over the pressure range relevant to altitudes in most residential locations of the US. As an example for Fort Collins at 5100 ft altitude this value results in a relative pressure loss of 17.8%. Extreme locations, such as Twin Lakes, CO can go up to 41.6% loss of pressure compared to 1 atmosphere.
From equation 4 we see that the heat added for the same volume at the same temperature at different altitudes is proportional with pressure, P, thus the same factor was taken into

account into the fitting formulas in equations 10-13 to describe the heat lost for a fixed volume rate *fR* at various altitudes.

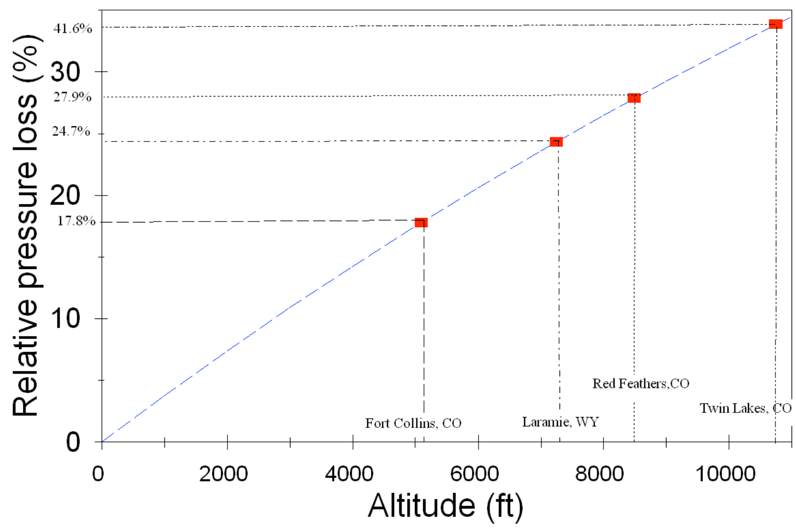

Fig 16: Relative pressure loss as a function of altitude following the barometric altitude formula for the altitude range of most homes in the USA. Fort Collins is at 5100 ft with 17.8% atmospheric pressure loss. Radon installations in Twin Lakes, CO were harder to accomplish than in Fort Collins.

ENERGY LOSSES FOR ALTERNATIVE RADON MITIGATION SYSTEMS

ERV/HRV systems are subject to similar type of heat losses as discussed, but the calculations here cannot be applied for the ventilation rates caused by these systems because in ERV/HRV systems a large fraction of the energy is recovered by an energy exchange medium, e.g. in the winter between a warm stream of air that is discharged out of the house to a cold stream of air that is pulled into the house.
The air exchange medium makes the calculation we have done here not applicable on that type of situation.

High energy efficient and electrostatic filtration to mitigate Radon Decay Products directly, not radon, do not exchange additional air with the outside environment, thus do not add additional energy losses beyond the already existing natural ventilation of the home. Thus from an energy efficiency point of view this technique maybe the most energy efficient method. However the number and power of ventilators may be very different from a radon ventilator in an ASD system and regular replacement costs of filters must be taken into account to determine operational costs.

A more in depth analyses for each situation separately is necessary to reach a valid conclusion.

TOTAL AVERAGE COST COMPARISONS OVER LIFETIME OF SYSTEM

Using a lifetime of a system of 40 years and for Fort Collins, Colorado which is in the middle of the HDD scale, the formula is used to calculate various components using equation 13 and the future variables for u, v, w from table 3. Durability of the ventilators is taken to have an average lifetime of 10 years. Installation costs are taken into account based on actual systems installed by us or others. In the histogram with the cost comparisons and power levels indicated along the base, the left four data each represent a system in Fort Collins without sealed slab or with finished basement that could not be sealed. The last data point represents the high energy efficient system presented as part of figure 6. The first data represent a system with the altitude correction. The second data represent a system without the altitude correction (sea level simulation), the effect is less than 19% because only a fraction of the energy losses involve air. It is clear that after 40 years the total cost per year to the home owners is lowest for the lowest power system, even when higher installation costs are included. In Figure 19 we have shown the cost development for the home owner including operational costs and ventilator replacement (proportionally taken into account) of each of these systems (calculated at sea level) accumulated over the years after installation. The open circles describe the cost tipping points where the occupant will have earned back their investment of the higher installation costs, after which it is clear that the system with lowest power ventilator will be most cost effective for the home owner. Radon levels are somewhat higher as indicated in figure 6. However even if higher

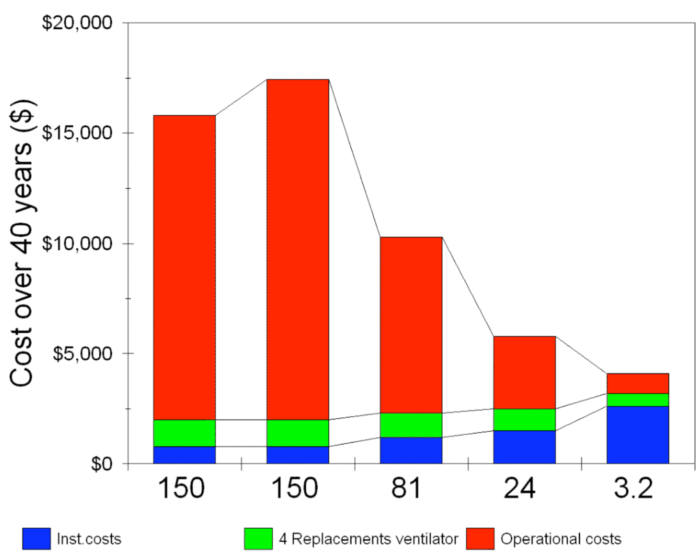

Figure 18 Four systems are compared on their 40 year total costs to the consumer. The left four represent non-sealed systems, the right-most data represent a high energy efficient system (See Fig. 6) system hermetically sealed with a double membrane under the slab. Left two data differ only in that the actual altitude of Fort Collins (5100 ft) was taken into account in the calculation for operational costs of the first data point..

power ventilators are used in the high efficiency systems they would not draw as much air from the basement as the system characteristics used in this calculation. From figure 19 we conclude that savings of radon mitigation systems are determined by how well they are installed, rather than any other parameter, specifically, they are not determined by the savings on installation costs.

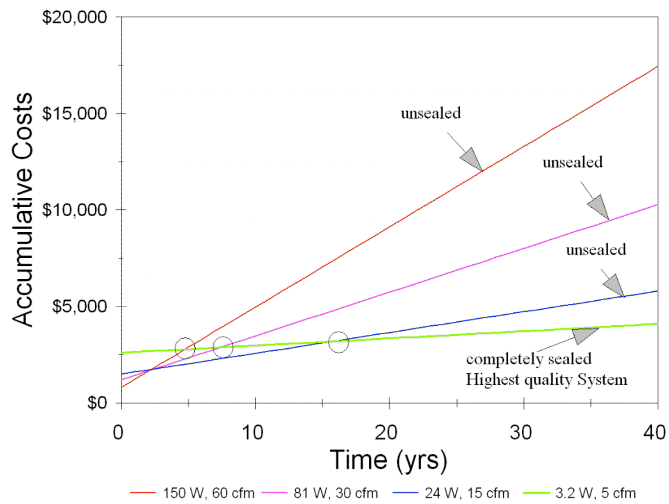

Figure 19 Comparison of accumulated costs in time to find out cross points for return on investment of a double membrane, completely sealed high energy efficient system compared to lower quality unsealed systems that have higher energy loss rates.

CONCLUSIONS

We considered various operational energy losses for radon mitigation systems. The convective heating, cooling losses and electrical costs were found to be the main energy losses. Measurements of air losses were discussed when gravel is applied below the concrete slab. It was concluded that substantial convective energy losses can be added to a house when proper sealing is not accomplished, or cannot be accomplished when the basement is finished. A case with an energy efficient system was discussed. It was concluded that although increased ventilation rates generate increased radon reduction, very satisfactory radon removal can be accomplished with extremely low power radon systems provided a high energy efficient passive radon mitigation system is installed during new home construction by conscientious mitigators.
In order to perform numerical calculations for a variety of locations in the United States and across all climate zones, fit parameters for outside air temperature conditions describing a modulation with a yearly cycle and a daily cycle were evaluated for each location. Numerical calculations were performed of additional operational energy losses and costs employing realistic utility cost rates for the next decade. A large variation of operational costs was found as a function of location. Total radon mitigation operational costs for the midrange and highest power ventilators were calculated to vary from less than one and one half times, in the warmest locations, to up to three times the electrical costs in the coldest locations considered. The smallest power commercially available

ventilator considered had the largest loss ratios to electrical costs across all regions which reached up to four and a half in the coldest location. General formulas were derived with effective parameters to describe the numerical operational energy loss and cost data in an effective way across the largest possible fraction of the heating zones and ventilator powers. The effective parameters in the formulas derived by a least square fit method compared well with the numerical data except for the most extreme weather locations. The operational costs formula was also employed to look at alternatives such as electrical heating and high energy efficient systems and this was compared to a normal heating system using natural gas. These results evaluating the formula also compared well with direct numerical calculations. It was shown that altitude effects which had been left out of all numerical calculations on purpose can be taken into account by using the barometric altitude formula. The size of these effects was evaluated. Energy losses of alternative radon mitigation such as ERV systems were discussed, and it was concluded that the formulas derived here do not apply to HRV and ERV systems due to the nature how they recover energy. Similarly it was concluded that RDP mitigation systems cause less energy losses but add operational costs due to frequent filter replacements.

A cost comparison over the lifetime of various systems in one location was made showing that over a forty year lifespan the costs saved by installing the highest energy efficient system during new home construction can be a four digit dollar amount. In this paper a case was made that for the highest quality radon mitigation systems one should look for the simultaneous “optimization” of four parameters, maximizing radon reduction, minimizing additional energy losses, minimizing noise effects and minimizing visual impact.

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