Sealing Crawl Space Exterior Walls and Soil Floor to Save Energy and Reduce Moisture of Floor Joists

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In attempting to reduce energy loss through the floor, it is often difficult and expensive to seal air leaks between the conditioned space and crawl space, and between the ducts and the crawl space. This seventeen house study in southern New Jersey found that it may be easier, cheaper and the resultant savings in energy more, if the crawl space is included in the conditioned space through insulating and sealing the crawl-space-to-outside envelope.

The purpose of this study was to modify weatherization practices in treating crawl spaces for several Atlantic Electric conservation programs. There are two concerns related to this strategy of sealing the crawl space to outside; a general belief that sealing a crawl space may increase the moisture content of the joists leading to degradation, and a perception it may be in violation of the Uniform Building Code. The results here, for crawl spaces that were sealed, show that moisture content of floor joists was significantly reduced.

For five houses with sealed crawl spaces, the variation in moisture content can be fully explained by the Effective Leakage Area of the crawl space to outside, supporting the hypothesis that the best way to reduce moisture is to eliminate the sources, and not to ventilate with moist air. Preliminary results show that this strategy saves energy as well as reduces moisture content of floor joists and is in some cases a better strategy for shell tightening and duct sealing than more traditional approaches. The estimated savings exceed $100/yr with a four year straight payback period.

Introduction

The intent of this study was to determine if it is feasible to seal a crawl space from outside air entry to save energy without increasing the moisture content of the wood members in the crawl space. It is often difficult and expensive to seal air leaks from the conditioned space to a crawl space since typically there are a large number of penetration sites and some are difficult to find. This is further complicated by supply and return duct leakage into and from the crawl space. Rather than attempt to eliminate these leakage points it may be easier, cheaper and the resultant savings in energy more, if the crawl space was included in the conditioned space—that is, the crawl space insulated and sealed from air leakage to or from the outside. This became evident during the implementation of a low income weatherization program, where houses were typically more than 50 years old with a large number of penetrations in the flooring in crawl space and basement overheads and large holes between basement and crawl space when both were present. In addition, ductwork often had leaky joints and the return a simple sheetmetal pan between floor joists. While new construction does not suffer from the same degree of shell/duct leakiness, some similar problems occur and, in time, homeowners may start cutting holes for wiring or other renovations. So this strategy may be appropriate for an energy efficient design for new home utility rebate programs.

There are two concerns related to this strategy. First, sealing a crawl space may increase the moisture content of the joists, leading to degradation. Second, and related to this concern, is that it may be in violation of the Uniform Building Code to seal foundation vents. It has been generally assumed that in summer the foundation vents allow outside air to dry out the crawl space, while in the winter crawl space ventilation is not required. Thus the rule is to open vents in summer and close them in winter. An exhaustive literature search by William Rose (1994) recently found that the practice of putting vents in the foundation walls of crawl spaces, and the building codes that address the standard area of ventilation for crawl spaces is not based on any scientific evidence. George Tsongas (1994) found that there is no evidence that passive ventilation and moisture is correlated in a 121 house study in the Pacific Northwest. His findings are that if a ground cover is present, vents are not necessary. The above recent findings support the work of several others who have suggested that passive ventilation of crawl space doesn't reduce moisture. These surprising results suggest that outside air coming in the open vents may result in elevated moisture content in wood floor joists if the dew point temperature is greater outside than in the crawl space. This was found to be the case in a small study conducted by Princeton's Center for Energy and Environmental Studies in New Jersey (Dutt et al. 1986) and by Sheltair in British Columbia (Moffatt 1991, Sheltair 199 1). Moisture content of the wood exposed to the crawl space air is directly dependent on crawl space relative humidity (RH). It is not necessary for there to be condensation on the wood, or for RH to be 100% for there to be a problem with potential rot, mold or mildew growth. There is a growing consensus among researchers that the best strategy to reduce moisture in crawl spaces is to eliminate the sources—in particular the moisture coming through evaporation from the soil, through the foundation walls, from outside air, from poor drainage, etc. This paper deals with one strategy to reduce these moisture sources for the Northeast region of the United States. However, it should also be appropriate for any region with outside conditions of high relative humidity.

Objectives

This study was designed in March 1991 to test the above hypothesis in southern coastal New Jersey, In particular the question to be answered is: Will a polyethylene moisture barrier covering the ground and block wall of the crawl space reduce the moisture content of the floor joists? And furthermore, by sealing the foundation (including closing the vents and covering with foam insulation) and insulating the foundation wall, will moisture from the outside air be eliminated and will existing air leaks between the house and crawl space be adequate in keeping the crawl space sufficiently dry? In addition, can moisture content of the floor joists in the crawl space be understood as being dependent on the connection with outside air as a moisture source?

The Study Group

To test this hypothesis seventeen houses with a total of twenty crawl spaces were studied. These houses were chosen as typical of the southern New Jersey region ranging in age from three to fifty years. The study group houses are all located in the coastal plain geologic region comprised of porous sandy soils with seasonally high water tables typically two to five feet below grade. All houses have a soil floor crawl space under at least a major portion of the house, with block foundation walls containing some operable vents.

Previous to any moisture mitigation and/or shell tightening eleven houses did not have a moisture barrier on the dirt floor of the crawl space. Of those, three had no insulation, six had fiberglass (FG) batts between floor joists (overhead), and two had at least some foundation insulation. Six houses had a partial or full moisture barrier over the dirt floor. Of those, one had polyethylene in one crawl space but not in a second. The remainder had full polyethylene on the floor with one having no insulation, one with FG falling down in part of the crawl, two with FG in floor joists in good condition, and one with both floor joist and foundation insulation.

Moisture content of the floor joists of the entire group was first determined and then the seventeen houses were divided into three subgroups. An attempt was made to assign houses to these three subgroups so each subgroup was individually representative of age, existing insulation and moisture barrier, geographic region and moisture content of floor joists. The first group remained untreated and served as a control group (#1). The second group had a 6 mil polyethylene moisture barrier placed over the ground and a polyethylene skirt hung down over the block wall, and is referred to as the moisture barrier group (#2). The third group had the same polyethylene treatment as the second with the addition of fire retardant FG insulation applied over the polyethylene on the block walls, vents covered with 1 inch of polystyrene insulation, and the crawl caulked at the rim, and is referred to as the full treatment group (#3). While each of these subgroups was representative of the general conditions, it was impossible to have conditions of moisture content exactly matched.

Pre-existing conditions were determined during September 1991, treatment was performed in October 1991, and post conditions were monitored commencing approximately 4 weeks after the completion by the weatherization crews and conducted until August 1992 with a total of ten site visits.

Measurements

Moisture

Moisture measurements were taken using a commercially available two pin resistivity instrument, and compensated for dry bulb temperature and species (assumed to be fir which is standard for this region). Moisture content of representative floor joists were measured at the rim, one foot in from the rim, and in the middle of the crawl (below and above the floor insulation if present). Measurements were taken from at least three representative joists for each type of location. If these readings were not within 2% of each other then more readings were taken to insure a more representative measurement. The locations were mapped and all subsequent measurements were taken in the immediate proximity for each visit. Weekly measurements, taken for one month (September 199 1) before any treatment, were used for a base data set. The houses were then treated according to whether they were in the control group (no treatment), polyethylene only group, or full shell tightening group. After a month six more sets of data were taken over a 9 month period representing winter, spring and summer conditions. Each data set was taken from the same joists and location so that variations would be attributed to the variables of treatment, temperature and RH alone. Dry bulb and wet bulb temperatures were taken for each crawl space on each visit using a sling psychrometer. While there may be large variations in outdoor dry bulb and wet bulb temperature readings day-to-day and during the day, only small variations were observed in the crawl spaces.

Effective Leakage Area

After full treatment of the five houses (seven crawl spaces) an Effective Leakage Area (ELA) was determined for air exchange between the crawl space and outside, the crawl space and house living space, and between the living space and outside. These measurements were taken using a standard balanced fan pressurization technique with two blower-doors; the first in an outside doorway to the living space of the house and the second in the crawl space to outside opening. In particular, when the living space and crawl space are individually pressurized to the same pressure, then the flow of air through the crawl space fan is indicative of crawl space leakage solely to the outside. Likewise, if the pressure of the living space is the same as outside (e.g., with doors and windows open), total flow rate through the crawl fan is the sum of the leakage to the living space and outside. Subtracting the first measurement from the second gives an estimate of leakage from the living space to the crawl space.

In two cases the entrance to the crawl space is located in the house, so a modified, yet similar, technique was used. A description of this modified technique follows: A second fan is installed between the interior to crawl space entrance. The fan is used to pressurize the crawl space to that of the house. This ensures there is no flow between the envelope and house (except through the fan). The flow through the second fan, then, is the induced flow rate between the crawl space and outside, while the flow through the first fan is the induced flow through the house envelope (not including the flow to the crawl space) plus the flow from the crawl space to outside. The second fan can then be used to repressurize the crawl space equal to outside ambient pressure. This results in a change in flow rate in the first fan equal to increased flow from the house to the crawl space and decreased flow from the crawl space to outside. Since the latter was already measured, the flow from the crawl space to house can be determined. This rate is also directly measured by the second fan. This can be checked further by measuring the flow through the first fan with the second fan removed and the opening of the crawl allowing the house and crawl space to be at the same pressure.

A standard fan pressurization method specifies the measurement of flow rate through the nozzle of a fan which is used to develop a pressure difference between the two spaces being tested (ASTM 1986). Typically six to eight pressure and corresponding flow measurements taken with the pressure differential ranging from 4 Pa to 50 Pa to estimate the flow rate through the nozzle, the pressure in the nozzle is measured and converted to a flow rate using the manufacturer's calibration. The leakage area of the house envelope was determined using this method. However, in three cases for induced flow rates between the crawl space and house or outside it was not possible to achieve large pressure differentials since the second fan had insufficient capacity, so the flow rate at 4 Pa. was measured directly in all cases to ensure uniformity.

To find the ELA the flow rate was estimated for a standard pressure difference, in our case 4 Pa, found using a statistical fit of the data to a semi-empirical crack flow model ($Q = cp^n$) for the house envelop leakage and measured directly for the other cases as discussed above. ELA is given by:

$$ELA = Q_4(d/2p).5 \tag{1}$$

where ELA = the effective leakage area, in m^2 (in^2)

Q_4 = the volumetric flow rate at 4 Pa (5.7×10^{-4} psig) in m^3/s (in^3/s)

d = the density of air, in kg/m^3 (lb/in^3)

p = the standard pressure difference, 4 Pa (5.7×10^{-4} psig).

Moisture content in the crawl space should correlate with the moisture source rate and inversely to the ventilation rate under equilibrium conditions. In our case it is more complicated since one of the moisture sources is outside air, especially in the summer months. For crawl spaces, in this study, there are four major sources of moisture—the moisture from soil and block, and outside and inside air. Removal of moisture is achieved through air leaving the crawl space through foundation vents and cracks and to air leaving to the living space through envelope penetrations and leaks in forced air distribution systems (if present). Since the total ventilation rate is equal to the sum of air source rates, moisture coming into the crawl space from outside air and ventilation both depend on the outside to crawl space source rate.

In particular, the relationships discussed above are summarized in a conceptual relationship for moisture content of the crawl space air and therefore the joists as:

$$MC \ \alpha \ (m_s + m_f + d_i Q_i + d_o Q_o)/(Q_i + Q_o) \qquad (2)$$

where MC = the moisture content of joist
m_s = the moisture source rate from the soil
m_f = the moisture source rate from the foundation
d_i = the moisture density of the house air
d_o = the moisture density of the outside air
Q_i = the air source rate from the house and ducts to crawl
Q_o = the air source rate from the outside to crawl.

Moisture source rates from the soil and block were not measured. Source rates from the outside and inside air also were not directly measured. So this neat conceptual model cannot yield quantitative insight. Instead, it is proposed that the effective leakage area be considered a substitute variable for both the air moisture source rate as well as the ventilation rate. For the ventilation rate the sum of the effective leakage areas from the crawl to outside and crawl to inside is used as a substitute variable. This assumes that the same fraction of holes leading to/from the crawl space from the house and to/from the outside are as likely to be a source as an outlet. While this is a gross simplification, there is no justification to chose any other particular fraction. In the winter, the stack effect might suggest that the smaller of the two ELAs (crawl to house or crawl to outside would best determine the ventilation rate. But for houses with forced air distribution systems, the stack effect is probably small compared with duct leakage. The stack effect is minimal in the summer, since there is very little thermal difference between outside and inside air. To further complicate matters, the ELA from the house to crawl includes both shell and duct leakage. Clearly, the ducts while pressurized or depressurized will have a larger leakage volume per ELA than the shell. For the purposes of this study these imperfections were ignored. It simply would not be possible to add any more terms to the above equation since the statistics would not support additional independent variables.

Replacing the source rate terms in the above expression with a factor (f) times the ELA, moisture content of the joists is given by the expression:

$$\begin{aligned} MC \ \alpha & (m_2 + m_f)/(ELA_i + ELA_o) \\ & + f_i(ELA_i)/(ELA_i + ELA_o) \\ & + f_o(ELA_o)/(ELA_i + ELA_o) \end{aligned} \qquad (3)$$

where MC = the moisture content of joist
m_s = the moisture source rate from the soil
m_f = the moisture source rate from the foundation
f_i = the moisture per unit leakage area from the house to crawl space
f_o = the moisture per unit leakage area from the outside to the crawl space
ELA_i = the effective leakage area between the house and crawl space
ELA_o = the effective leakage area between outside and crawl space.

The expectation is that the first term is small in the above expression for MC for fully treated crawl spaces since the moisture barrier should almost eliminate those sources. In summer it is expected that the second term dominates, especially for air conditioned houses. In winter it is not clear which term is most significant since both outdoor and indoor air carry moisture. To complicate this the ELA ratios in term #1 and #2 are analytically related (the sum is always = 1). So the separate effects of terms #1 and #2 cannot be statistically separated.

In any event, the purpose of this model is to develop insight into mechanisms of moisture content of joists. It should be viewed only as a conceptual model.

Results

Moisture Content

While no condensation was actually observed on crawl space joists, in several cases the moisture content approached saturation levels. In two crawl spaces very high moisture content (approx 32%) was found pre-existing in one floor joist each. In addition, several other joists had near saturation values (24-28%). One case remained in the control group and the other in the fully treated group. The former reduced during the winter and returned to the same very high values (near saturation) the following summer. The latter likewise reduced in winter but did not return to these high values in the following summer; instead of the previous level of 32%, moisture content in the floor joist came up to only 23%.

It is somewhat surprising that the crawl space temperature was not substantially different in the fully treated group compared with the other two (Table 1). However, there are competing mechanisms in determining temperature increase or decrease in these retrofits. The insulation on the foundation wall reduces conduction gain and loss. However, the reduction in leakage through the foundation not only reduces interchange between the crawl and outside but could also reduce the interchange between the house and crawl space. Furthermore, five of the seven crawl spaces for the full treatment group had existing floor insulation, so the floors were fairly insulated from

Table 1. Moisture Content of Wood Joists Aggregated Based on Subgroup

	T_{dry} (°F)	T_{wet} (°F)	RH (%)	Moisture content (%) Rim	1-ft-in	Middle Below	Above Insulation	Julian Day
Group 1 - Control (untreated)								
Pre	74	68	75	17.8	17.1	17.8	19.2	-118
	73	67	76	17.3	18.5	17.9	18.0	-111
	70	64	73	17.4	18.9	17.9	16.8	-104
	68	61	70	16.4	18.1	17.2	15.3	-97
Post	59	51	59	14.1	14.2	11.5	11.2	-27
	59	53	67	15.0	13.7	11.8	14.5	3
	54	45	52	12.6	11.1	9.3	8.5	28
	58	50	57	13.7	12.9	11.6	11.8	91
	72	67	77	15.8	18.3	18.6	17.2	192
	72	67	78	16.5	18.8	18.2	14.7	222
Group 2 - Moisture barrier (polyethylene on bare soil and overblock)								
Pre	71	66	77	14.8	15.5	16.9	19.5	-118
	71	65	75	14.2	16.2	16.5	19.8	-111
	70	65	77	13.9	16.1	17.2	16.8	-104
	69	65	79	14.7	16.2	16.8	16.3	-97
Post	62	52	54	11.7	11.3	10.6	11.3	-24
	62	54	59	11.8	10.5	10.5	10.4	3
	60	48	41	9.8	9.1	9.1	8.0	29
	62	52	53	10.9	9.9	9.0	9.2	97
	72	67	77	14.0	15.6	15.4	14.0	193
	71	65	73	13.5	15.3	15.5	12.5	222
Group 3 - Full Treatment (moisture barrier plus shell tightening and block insulation)								
Pre	71	65	75	15.3	18.4	19.9	17.2	-118
	70	64	72	15.6	17.8	18.9	18.2	-111
	69	62	72	15.3	18.6	20.8	14.9	-104
	68	61	71	15.7	18.2	19.7	14.8	-97
Post	61	51	50	12.4	11.8	11.6	11.0	-27
	61	54	60	13.2	11.3	11.3	10.9	3
	56	46	47	11.6	10.1	10.2	8.9	28
	60	50	49	13.0	10.8	10.4	10.4	88
	68	62	75	15.0	16.1	16.6	14.3	192
	71	65	73	15.2	15.9	15.8	11.9	221

conduction losses to the crawl spaces from the start of the study, even before foundation insulation was installed.

Crawl space wet bulb and dry bulb temperatures were converted to a RH for each visit and crawl space. In the full treatment group the pre-treatment RH ranged from 59% to 94%. In the following summer the range was narrowed-61% to 85%. The high values in the range are troublesome since they are indicators of potential problems. Indeed, it was the crawl spaces at the high end of the RH range that had joists near saturation during the pre-treatment period.

For each of ten site visits the statistical mean, for each group, of crawl space RH, and moisture content of the joists in the three locations (rim, one foot in from rim, middle—below insulation, and middle—above insulation if present) is presented in Table 1.

Figure 1 is a plot of the relative humidity. Figure 2 is a plot of joist moisture in the center of the crawl space, and Figure 3 an average of the three locations common to all crawl spaces. The first four visits represent pre-existing conditions during the latter part of the summer and are summarized as an average plotted at approximately Julian day = -100. The remaining six visits represent post-retrofit conditions and are connected by a line.

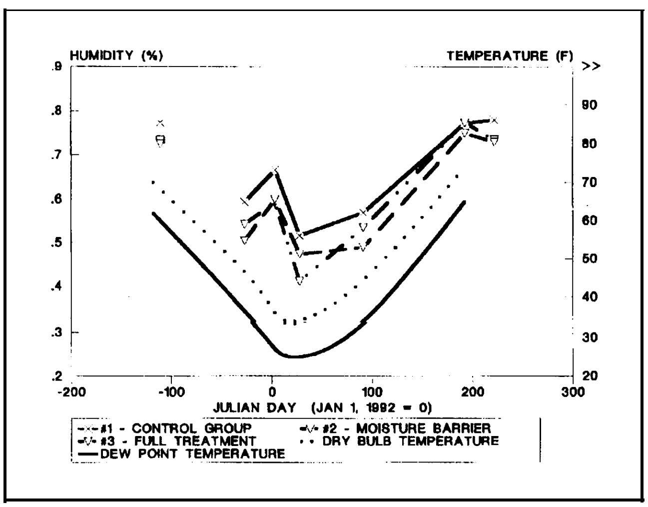

Figure 1. Relative Humidity in Crawl Space, Outside Dry Bulb and Wet Bulb Temperatures for Pre and Post Treatment

The four heating season visits are referred to as winter months and the two cooling season visits are referred to as summer months. There is a large seasonal variation but it is clear that the moisture content in the treated groups is reduced. Except for the rim joist data, all full treatment crawl spaces resulted in reduced moisture content comparing the summer data post-retrofit to pre-retrofit.

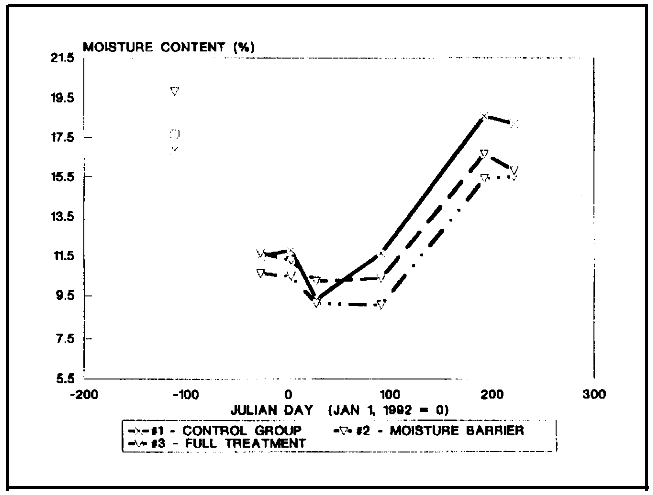

Figure 2. Moisture Content of Joists in Middle of Crawl Space (Below Existing Insulation if Present) Pre and Post Treatment

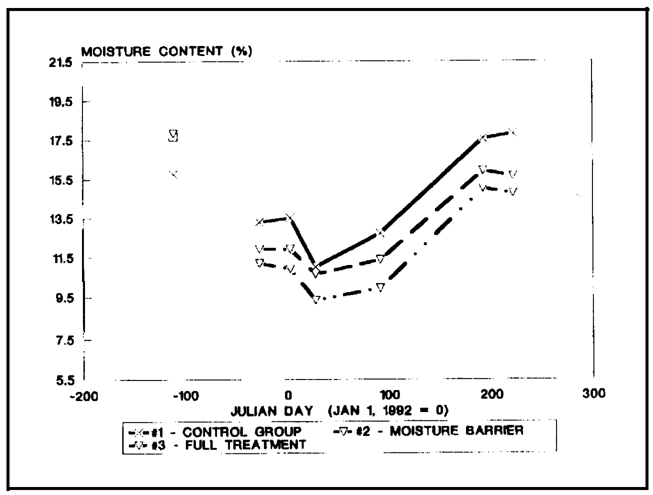

Figure 3. Average Moisture Content of Three Locations in Crawl Space Pre and Post Treatment

The general rule of thumb, that the moisture content should be under 20% for at least part of the year to insure rotting does not occur, was met in all but one untreated house. Mold and mildew were observed in a number of crawl spaces and were clearly related to the high RH. No measurements were taken to quantify these observations.

There was an attempt to match the groups so that pre-existing conditions were the same. However, as seen in Figures 1-3, the groups did not have identical values of moisture content and RH. To compare the effect, the mean value of moisture content for each group was determined for pre-existing conditions in September (four visits). This mean value was used as a normalizing factor for that group, Thus, data for each group started out with a normalized mean value of 1.0 for the four pre-treatment visits.

To assist in comparing the two treated groups to the control group, values for each visit were further normalized by the value of the control group during each of the six post retrofit visits. Thus, if the treated group experienced the same seasonal changes of the control group, it would have a value of 1.0 for the entire testing period. Any value less (or greater) than 1.0 represents the fraction of moisture content after retrofit compared with that expected if there were no change. These renormalized results are shown in Figures 4-6 for the six visits after treatment.

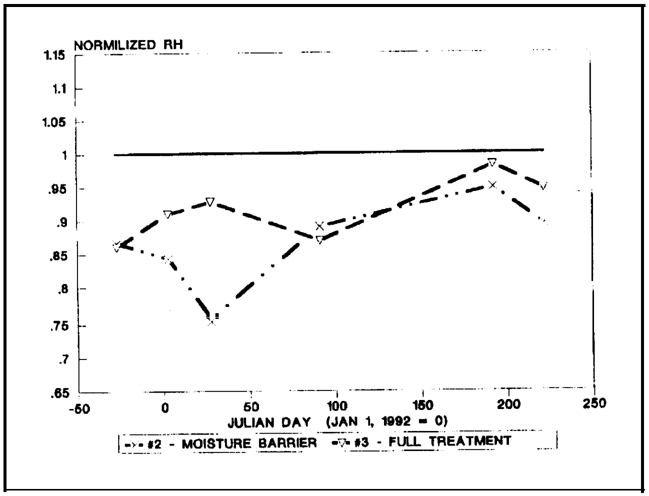

Figure 4. Relative Humidity Normalized to Control Group and Initial Conditions Post Treatment

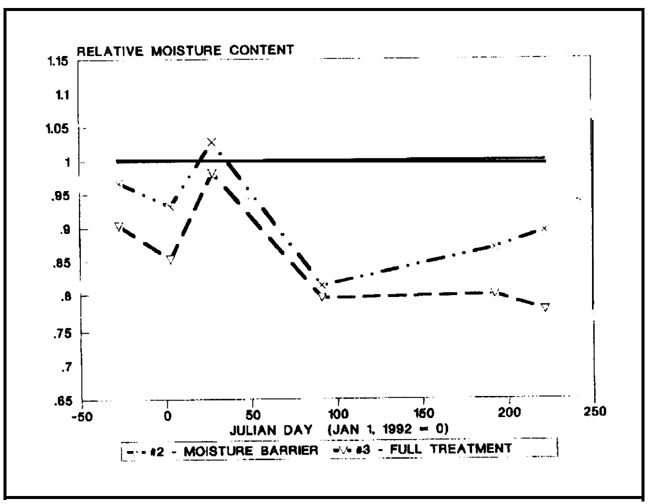

Figure 5. Moisture Content in Joists in Middle of Crawl Space Normalized to Control Group and Initial Conditions Post Treatment

In general, moisture content is reduced for both the moisture barrier group (#2) and the full treatment group (#3) in both summer and winter. There is no absolutely clear advantage for the full treatment group from this perspective. This supports earlier studies cited that have found a moisture barrier alone reduces moisture content of wood joists. But the result reported here is significant in that it shows shell tightening does not increase moisture content, which is the hypothesis being tested. The only exception is that the rim joists marginally had an increase in moisture content. This did not pose a problem since the rim joists had low moisture content.

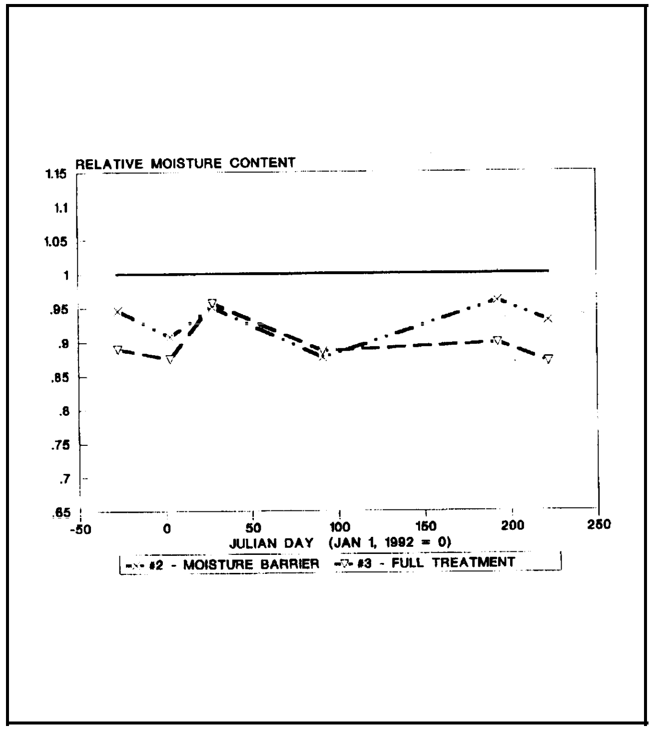

Figure 6. Average Moisture Content of Three Locations in Crawl Space Normalized to Control Group and Initial Conditions Post Treatment

Effective Leakage Area

Table 2 summarizes measurements of ELAs for the five fully treated houses after retrofit. The conceptual relationship, developed earlier between MC and ELAs, suggests a correlation of MC with total ELA (sum of crawl space to outside and to house), and to ELA ratio (ELA of crawl-outside to total ELA). If a stack effect were to dominate then either the crawl-outside ELA or crawl-house ELA would dominate. All of these ELAs strongly correlate to each other and therefore cannot be thought of as independent variables.

The results of these correlations are summarized in Table 2. It is clearly seen that the highest moisture levels are in houses with the largest crawl to outside ELA.

There seems to be less of a relationship with house-to-crawl ELA. A linear regression analysis was performed individually on these two variables, as well as the sum and the ratio of the crawl-to-outside ELA to the total ELA as

Table 2. Analysis of Effective Leakage Area (ELA) and Moisture Content of Fully Treated Houses

	ELA (cm^2)					Moisture Content (%)				
						Summer		Winter	Summer	
House ID	House to Out	Crawl to Out	House to Crawl	Crawl ELA Ratio	Total to Out	Pre	Post	Post	Post Minus Winter	
S	1271	97	348	.217	445	13.9	11.9	10.1	1.8	
P	2690	271	787	.256	1058	14.8	13.6	10.0	3.6	
M	2528	116	697	.143	813	16.3	11.3	8.6	2.7	
R	1393	458	271	.628	729	23.8	18.6	13.5	5.1	
H[(a)]	1319	542	116	.824	658	19.7	18.7	13.5	5.2	

Statistics (R^2)

Statistics (R^2)	Crawl ELA ratio	Crawl to out ELA	House to Crawl ELA	Total ELA
summer (post)	.94 (.98)[(a)]	.96 (.95)	.51 (.29)	.002
winter (post)	.92 (.98)	.86 (.80)	.68 (.52)	.05
summer - winter (post)	.80 (.76)	.95 (.76)	.24 (.04)	.05
pre - post (summer)	.20 (.01)	.21 (.00)	.09 (.01)	.001

(a) R^2 values in parenthesis are without house "H" data.

suggested earlier (referred to as ELA ratio). The results in Table 2 show a high R^2 for crawl-to-outside ELA as well as the ELA ratio fit to post summer and winter retrofit data, while house-to-crawl ELA and total ELA exhibits a low R^2. A plot of moisture content vs. crawl ELA ratio is presented in Figure 7.

Four of the five full treatment houses (representing five of the seven crawl spaces) have forced air distribution systems located in the crawl space (for both heat and air conditioning) while the fifth heats with baseboard hot water and cools with the occasional use of window air conditioners. For the four houses with an air distribution system a similar statistical analysis of the crawl space data is reported in Table 2 in parentheses. These results for post retrofit summer and post retrofit winter show a very high R^2 (.98) for ELA ratio while the R^2 for crawl-to-outside ELA fit is .95 for summer and .80 for winter.

Given the high correlation between these two independent variables, these results support the model proposed earlier (primary source of moisture is from outside air with dilution from inside air). Furthermore, since outside air has a much lower moisture content in winter, it is expected that the primary difference between summer and winter moisture content is due to the leakage from outside. The correlation with the summer winter difference in moisture content of the joists with the four different ELA factors shows this to be the case. In particular, the R^2 value for crawl-to-outside ELA is .95 while to ELA ratio is .80 (.76).

A test of significance (two tailed t-test) was performed on the two sets of data found in Table 2. A 95 percentile confidence interval was employed to reject the null hypothesis. As is clear from the low R^2 values, house-to-crawl ELA and total ELA are rejected as insignificant variables by this criterion. Likewise, none of the ELAs can predict the pre-post reduction in MC. The ELA ratio is significant in predicting both the MC post retrofit for the five houses and subgroup of four houses both in

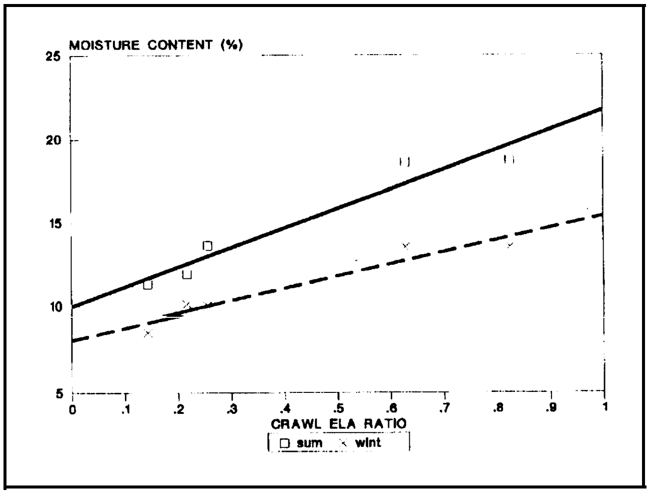

Figure 7. Dependence of Average Moisture Content of Three Locations in Crawl Space in Five Fully Treated Houses on Crawl ELA Ratio

summer and winter. This is also true for the crawl-to-outside ELA except for the four subgroup case in winter. Finally, the difference between MC in summer and winter can be explained by the crawl-to-outside ELA, but not the ELA ratio.

There is no clear correlation of the reduction in moisture content between pre and post retrofit with any of the ELA values above as seen in the extremely low R^2 values. This is expected since any reduction would be caused by the reduction in outside air leakage into the crawl space and also reduction of moisture from the soil. Neither of these reductions would be captured by the post retrofit ELA.

Actually the large R^2 values for the post retrofit conditions on the crawl ELA ratio and crawl-to-outside ELA is surprising. This fit neither takes into account how much leakage to the house is in the ducts and how much in the shell, nor does it take into account the size of the crawl spaces. This surprising result may be fortuitous. It is important to be cautious, and only treat these results as supporting a conceptual model.

These results show that once the moisture source from the soil is eliminated, the major source of moisture is from outside air. And leakage to the house plays a smaller but definite role in reducing the moisture. However, it is not clear when and to what degree the stack effect is dominant and when the conceptual model for MC developed earlier is dominant. The high correlation between these two ELA variables (R^2 = .94) made it impossible to determine between these mechanisms. In addition, that a forced air distribution system is a major factor in reducing MC is only speculative, since a statistical analysis cannot be performed on this small data set.

Estimated Energy Saving

As a result of this study, all of the homeowners without the full treatment measures opted to have their crawl spaces fully treated to bring them up to the group #3 level. This was accomplished in August 1993. As a result, a statistical measurement of energy savings is not possible to report at this time. However, it is possible to estimate what they weld have been for the five houses that were fully treated in this study. The savings are estimated to be insignificant for two of the five houses. In both cases the temperature in the crawl space seemed to be the same as the controls, and the house to crawl ELA was small while the crawl to outside ELA remained large. The weatherization crew in the first case did not seal all the vents, and in the latter case vent plugs were only loosely fit. As a result, infiltration reduction would be small.

In the other three cases the average temperature in the winter was 8°F higher than in the average of the control groups. In addition an estimate of the reduction of passive infiltration can be made by comparing the above ELAs. Since there are approximately 100 days of heating demand where the temperature in the crawl space is at an elevated temperature, then the floor will experience approximately 800 fewer Degree Days. For one of the houses the floor R-value is estimated as R-2, for a second part was insulated and estimated to have an R-10 under that part, and the third fully insulated with an R-11. And reduced infiltration was estimated by using the reduced ELA for the three and assuming that the reduced infiltration is $Q_{50}/20$. This undoubtedly underestimates the ventilation savings since it does not explicitly take into account duct losses. The savings in the summer were estimated with less certainty, but assuming the same infiltration value. The results of this analysis is shown in Table 3. The first house has a geothermal heat pump, the second a gas fired boiler, and the third a oil fired boiler. As is seen, the straight payback of the two traditionally heated/cooled houses is approximately 4 years, while the retrofit of the efficiently heated/cooled house has a straight payback of 6.5 years.

Discussion

Of the five houses that were fully treated, two previous to retrofit had well-installed FG insulation between the floor joists and had a small ELA between the house and crawl space. Of the three remaining houses, two crawl spaces had partial FG insulation, one had complete insulation and all three had a much larger ELA between the house and crawl space. The strategy of sealing the crawl space and placing a moisture barrier of the soil floor as a means to reduce moisture and save energy is viable for those houses with a large leakage area between the house and crawl

Table 3. Calculation of Energy Savings for Three of Retrofit Group with Large House to Crawl ELA

House ID	Heat/Cool	Conduction Savings Fuel		Infiltration Savings Fuel		Total	Retrofit Cost	S.P.
S	geotherm. hp	240 kWh	$24	400 kWh	$44	$68	$441	6.5 yr
P	gas/elec ac	93 T	$65	97 T/400 kWh	$120	$185	$728	3.9 yr
M	oil/elec ac	30 g	$33	80 g/450 kWh	$146	$179	$752	4.2 yr

space. Two of the retrofits had a small ELA between the house and crawl space and only received a marginal benefit-slightly reduced moisture of very saturated wood joists but no noticeable energy savings. The remaining three, with a large ELA between the house and crawl space saw a major reduction in energy consumption. After retrofit, the temperature of the air in the crawl space of the former subgroup closely followed the average temperature of the two other groups (control and moisture barrier). The latter subgroup was 8°F warmer during the winter months and 1°F cooler during the summer months than the former subgroup. The finding that the latter subgroup had a lower moisture content of floor joists than the former subgroup, further supports the conclusion that the air exchange between the house and crawl space has the effect of drying the wood members. This strongly suggests that treating the crawl space within the conditioned space envelope, results in lower moisture content of wood joists and saves energy but is only a viable strategy if the crawl to house ELA is substantial.

Conclusions

In all cases—whether a moisture barrier was placed on the crawl floor and over the block walls with vents left open, or whether a full shell tightening with insulation over the block wall was applied—there was no increase in moisture content which would lead to degradation of the joists. This was the original and primary purpose of the study. But there are other significant conclusions which apply to a climate similar to New Jersey's.

1. As is expected for the climate in New Jersey, once a moisture barrier is placed, moisture is not a problem in crawl spaces in the winter months regardless of whether the vents are closed or open.

2. Once a moisture barrier is placed on the bare soil floor variation in moisture between houses, in both summer and winter, is best understood as due to the variation in the rate of outside moist air coming into a cooler environment in the crawl space. The correlation with the crawl ELA ratio and average moisture content in the five treated crawl spaces support this conclusion.

3. A moisture barrier placed over bare soil reduces a major source of moisture as fully expected. This source is approximately equal to the source of moisture in the outside air.

4. Although somewhat speculative, the air distribution system appears to play a role in reducing moisture levels in the crawl space, Whether this is due to depressurization or pressurization is uncertain. In either case more interior air is pulled into the crawl space. The results presented here are not based on a statistical analysis since the data set is too small. A larger study would be required to separate the effect of duct leakage from that of house to crawl.

This work was performed on already existing housing but should be generally true for new building as well. While energy savings have yet to be measured, other studies have found savings and calculations presented here supports this for those houses with a large crawl to house ELA. The measured energy savings will be reported at a later date.

The results here suggest that a strategy to save both energy and control moisture in crawl spaces is to design an effective moisture barrier. The crawl space should be totally sealed, with no operable vents, and some conditioning (either from the interior space or forced air distribution system) should be included to insure the crawl space is dried.

As a final note other benefits accrue from an insulated sealed crawl space. Water pipes are protected from freezing and drier crawl spaces don't smell as musty.

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