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EVALUATION OF A GROUND COUPLED AIR-TO-AIR (CRAWL SPACE) HEAT PUMP

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INTRODUCTION

While a heat pump is a desirable heating unit due to a seasonal coefficient of performance (COP) in excess of 1.5 in moderate climates, its performance decreases in the coldest part of the winter when the heating load is greatest. Both the COP and capacity of the machine decrease as the outdoor temperature decreases. Auxiliary resistance heaters must then be used to provide the deficit capacity. The overall COP of the unit then approaches 1.0.

Another factor that degrades the performance of an air-to-air heat pump is the requirement for the heat pump to defrost. Defrost becomes necessary when high humidity conditions exist and a layer of frost forms on the outdoor heat exchanger, blocking the airflow over the heat exchanger. When this occurs, the heat exchanger effectiveness is drastically lowered, so the COP and capacity of the machine are reduced. Additional energy must now be spent to defrost the outdoor heat exchanger to bring the performance and capacity of the machine back up to a normal level. The requirement for such cycles reduces the overall average efficiency of the machine.

The purpose of this study was to perform an initial investigation of the use of ground source energy available in the crawl space of a single-family dwelling. Two modified installations of a conventional air-to-air heat pump were investigated. The modified installations that were investigated were the single-pass and recirculating crawl space air-to-air heat pumps. The single-pass crawl space heat pump pulls ambient air through the crawl space to the outdoor heat exchanger where it is exhausted back to ambient air (Fig. 1). The proposed recirculating crawl space heat pump installation makes use of a sealed crawl space and appropriate ducting to draw the air from one part of the crawl space and exhaust it to another part for a continuous recirculation of the crawl space air (Fig. 2).

The single-pass installation was experimentally tested at a residence in Oak Ridge, TN (The Betz residence). The recirculating installation was investigated by analytical models based on the experimentally determined total resistance value from the soil to the crawl space air determined from the single-pass installation test (1). An analytical model investigation of the installation made use of the National Bureau of Standards Loads Determination computer program, NBSLD (2) to generate the hourly heating load for the thermal envelope, with input parameters based on the test house in Oak Ridge, TN, and the most recent weather data available that best matched the weather experienced during the time of experimental data collection. These data were used to determine the load requirements of the heat pump system.

A program, CRAWLTEMP was written to perform a heat balance on the crawl space to determine the dry bulb temperature of the crawl space, calculate the heat fluxes and mass transfer across the boundaries of the crawl space, and predict the net savings of the crawl space heat pump.

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Single-Pass Crawl Space Air-to-Air Heat Pump

The single-pass crawl space heat pump can be installed in a new residence or as a simple, low cost retrofit to an existing home built over a crawl space. The purpose of this installation is to raise the temperature of the air passing over the outdoor heat exchanger. This is accomplished by ducting ambient air through the crawl space to the outdoor heat exchanger via the existing air handling unit. In drawing ambient air through the crawl space, heat transfer takes place from the ceiling, the floor, and the walls of the crawl space. The ceiling of the crawl space is the insulated floor of the structure, and the floor of the crawl space is an unfinished dirt floor with a plastic vapor barrier stretched over the surface. Temperatures measured to perform a heat and mass balance of the crawl space air were of the thermal envelope, crawl space, and ambient air. The temperature of the soil at an 0.46 m (18-inch) depth was periodically measured to verify the numerical algorithm SOILTEMP discussed below. The flow rate over the outdoor air handling unit was also measured.

Experimental Configuration

There are five major components that varied from a standard installation of a split-package heat pump in the system installed in the 116 m^2 (1248 ft^2), single-floor occupied dwelling in Oak Ridge, TN. These are the air collection chamber, the ambient air inlet, the defrost fan, the mode switch, and the outdoor package. The air collection chamber is an insulated box which allows the particular outdoor unit to be interfaced with a hole in the crawl space wall and the ambient air inlet. The mode switch is a plywood damper which selects whether the outdoor unit will receive ambient air or air from the crawl space. The defrost fan was found to be necessary to remove the water that occurs during a defrost cycle from the air collection chamber. This water vapor, should it propagate to the crawl space, could cause a deterioration of the structure. It is important that the air collection chamber and all associated ducting not reduce the airflow rate over the outdoor heat exchanger. This would reduce the ability of the outdoor unit to extract the required amount of heat from the air, hence reducing the overall performance of the machine as specified by the manufacturer. The above discussion covers the interface between the outdoor unit and the crawl space. In the test installation in Oak Ridge, the available ventilation holes on the end of the structure where the outdoor unit was installed were blocked to prevent short-circuiting of ambient air. However, there was sufficient entry area left open to prevent any additional pressure drop through the inlet holes. This configuration gave 16 air changes per hour flow of air. Here again, it is still important to maintain the required airflow rate over the outdoor heat exchanger.

Insulation Requirements

In using the installation of the single-pass crawl space heat pump, it is necessary to insulate the ceiling of the crawl space, which is the floor of the thermal envelope. This is necessary to prevent a large heat loss from the structure to the crawl space. In the test house, the total thermal resistance was composed of R-11 insulation, the carpet and mat, the subfloor, the hardwood floor, and two convection boundary layers. This represents an overall heat transfer resistance (3) of 3.07 m^2C/W (17.45 h ft^2 F/BTU). In most structures of this type, the crawl space also contains large amounts of plumbing. All plumbing lines should be insulated in such a way that it ties them to the thermal envelope of the house, so that heat loss from the house will keep the pipes from freezing in the event that the crawl space temperature drops below 0C (32 F). It is also necessary to insulate all of the traps in sewer lines, as these areas can freeze as well as the water pipes. In the event that the water is installed in the crawl space, it is recommended that the water heater have additional R-11 insulation applied to the outside of the jacket to reduce the amount of heat loss from the water heater. The insulation of the floor, the piping, and the water heater was done in the Oak Ridge house to minimize the heat loss from the thermal envelope of the house, to prevent the pipes from freezing, and to minimize the heat loss from the water heater.

Infiltration Precautions

In the test house, an investigation for holes in the floor of the thermal envelope was made. Any holes that were found were plugged. Also, an infiltration test was run to determine if there was an increase in infiltration when the outdoor unit was actively pulling air through the crawl space. No increase in infiltration was found. Should this precaution not be taken, a large amount of heat could be lost from the thermal envelope to the crawl space due to the increase in infiltration through the floor of the thermal envelope. A decrease in pressure in the crawl space is associated with the operation of the outdoor air handling unit. In the test house, the decrease in pressure between the thermal envelope and the crawl space was found to be 3.47 Pa (0.015 in H_2O). This decrease in pressure is a driving force for air to move from the thermal envelope to the crawl space.

Experimental Energy Balance

By using collected dry bulb air temperature data, some of which are shown in Figs. 3-6, velocity measurements, and the heat pump run time, a heat and mass balance is performed on the air within the crawl space. By using a conduction heat transfer equation of the form everything is known except the heat flux (Q) from the soil. Solving Eq 3 for

$$\text{heat flux} = \frac{\text{area} \times \Delta\text{temperature}}{\text{total resistance}}, \tag{1}$$

and an energy transport equation of the form

$$\text{energy} = \text{mass flow rate} \times \text{specific heat} \times \Delta\text{temperature}, \tag{2}$$

and writing the steady state energy balance

$$0 = Q_{wall} + Q_{air\ mass} + \dot{Q}_{soil} + Q_{floor}, \tag{3}$$

heat flux from the soil and substituting back into Eq 1, it is found that the total resistance value of the soil and the soil temperature is unknown. Algorithm SOILTEMP was written from the information given in Ref. 4 (as discussed below) to calculate the soil temperature at a depth of 0.46 m (18 in). This soil temperature at 0.46 m was taken as a reference point to define an effective thermal resistance from 0.46 m deep to the crawl space air temperature. The effective resistance value consists of the convection boundary layer, the plastic moisture barrier, and 0.46 m of soil. This effective resistance value was calculated from the above equation on an hourly basis from the temperature and flow rate data collected, and these values were averaged. The total effective resistance value for the soil was found to be 0.0687 m^2C/W (0.39 h ft^2 F/BTU) for this geographical location. This effective resistance from the soil can then be used with temperature calculated at a 0.46 m depth to predict crawl space heat pump performance at any time of the year and for any weather condition at the test site.

Algorithm SOILTEMP calculates the soil temperature for any depth to 18 m (60 ft) based on the input parameters of monthly average ambient dry bulb temperatures and the diffusivity of the soil. The following equation from Ref. 4 for a semi-infinite solid was used to calculate the soil temperature at a depth of 0.46 m.

$$T = A - B \exp\left(-\sqrt{\frac{\pi}{D \cdot 8766}} \cdot x\right) \cdot \cos\left(\frac{2\pi\theta}{8766} - \sqrt{\frac{\pi}{D \cdot 8766}} \cdot x - P\right), \tag{4}$$

T = monthly average earth temperature (C),
D = thermal diffusivity of the earth (m^2/s),
θ = the time coordinate which is taken as zero on January 1 (h),
A = annual average earth temperature (C),
B = annual amplitude of the monthly average temperature cycle (C), P = phase angle of the earth temperature cycle (radians),
x = depth in the soil, from the surface, of the calculated temperature "T" (m).

The values for A, B, and P are determined by a least squares method as per Ref. 4 and the thermal diffusivity must be determined in the laboratory or from the literature. From Ref. 4, the calculated soil temperature is a weak function of soil thermal diffusivity where a variation from 0.52 mm^2/s to 1.04 mm^2/s (0.02 to 0.04 ft^2/h) gives only a 1.1C (2 F) shift in soil temperature.

The temperatures that SOILTEMP predicted were checked against monthly measurements at two locations, in the crawl space at a depth of 0.46 m and 15.25 m (50 ft) from the house at a depth of 0.46 m. These results are given in Table 1. It was found that the predicted temperature fell well within a normal 10% error, and the temperature of the soil in the crawl space differed only by 0.5 - 1.0C from that of the soil 15.25 m away from the structure.

Looking at experimental temperature data* for the single-pass geothermal operating mode (Fig. 3-6), it can be seen that the crawl space temperature fluctuates with the outdoor air temperature. However, the amplitude of the fluctuations is considerably less as compared with outside air temperature. Another very important observation is that as the outside air temperature goes lower, the difference between the crawl space temperature and outside air temperature becomes larger. This higher than ambient temperature increases the performance and capacity of the heat pump at the time when the heat pump needs help the most. Looking at the lowest ambient air temperature between day 1 and day 2 in Fig. 3, it is noted that the outdoor heat exchanger is receiving about -1.1C (30 F) air as compared to the below -17.8C (0 F) outside air temperature. Manufacturer's heat pump performance data show that performance and capacity are increased substantially.

It is important to establish that the high temperature of the crawl space is not generated by heat losses from the thermal envelope. Typical values calculated from Fig. 3 for the temperature data between day 1 and day 2 when the outdoor air temperature dropped below -17.8C (0 F) are as follows: heat through the floor of the thermal envelope, 861 W (2939 BTU/h); heat through the walls of the crawl space, -2284 W (-7795 BTU/h), energy associated with the mass flow rate of air, -14,861 W (-50,719 BTU/h); and heat from the soil, 16,284 W (55,575 BTU/h). This shows, at one of the least desirable outside air temperatures, that the majority of the heat comes from the soil.

The next question is how much load is added to the thermal envelope due to the lower crawl space temperature. Due to the inability to collect temperature data when the crawl space is operating in a normal ventilating configuration with a similar outside air temperature as in the single-pass crawl space installation, it is impossible to give an absolute difference in crawl space temperature of the two installations. However, based on available crawl space data taken at different outside air conditions, the crawl space temperature would be approxmately 1.5 - 2.0C (3-4 F) lower which places an additional load of about 66 W (225 BTU/h) on the thermal envelope.

Analytical Heating Season Predictions

Due to the inability to have two identical thermal systems, one using the single-pass heat pump installation and the other having a normal free-ventilating crawl space, it was necessary to create an analytical solution that would predict the effect of the different types of heat pump installations. After an analytical solution was found, the results were verified when possible with experimental data. The method of verification will be discussed later.

As described earlier, the most important parameter in heat pump performance for a given thermal envelope temperature is the temperature of the air that passes over the "outdoor" heat exchanger. The following discussion shows how the crawl space temperature was predicted and how the performance predictions were made.

NBSLD was used to determine the heating and cooling loads of the thermal envelope. The input parameters for the program are characteristic of the particular structure, along with its geographic location and orientation. A weather data tape is also one of the necessary input parameters.

Weather tapes are available for various cities in the United States. The latest weather tapes available were for the year 1955. A visual scan was made of the ambient air temperature history that simulated the weather that occurred in 1977 in Oak Ridge, TN. The 1955 Minneapolis, MN yearly weather tape simulated Oak Ridge weather the closest. It is noted that a weather tape which covered the same time period as the experiment would be preferred, but none was available.

NBSLD passes to program CRAWLTEMP the heating and cooling loads of the thermal envelope, outside air dry bulb and wet bulb temperatures, and the barometric pressure. Having calculated the heating and cooling loads of the thermal envelope and using the

*Transient effects were minimized by allowing the heat pump to operate in the single-pass mode for a month prior to collecting temperature data.

weather data, a heat and mass balance is calculated for the air of the crawl space. This process is carried out in the same manner as in the experimental section; however, instead of the heat flux from the soil being unknown, the temperature of the crawl space is unknown. The crawl space temperature is solved in the energy balance equation using the previously calculated total resistance value of the soil and the method of calculating the temperature of the soil at 0.46 m. System program YNEWTN (5) is used as a piecewise cubic interpolation routine to approximate numbers between known or given data points of heat pump performance data and monthly predicted soil temperatures. The results generated by CRAWLTEMP are given in Table 2. The comparison of the predicted crawl space temperature to measured crawl space temperature was made difficult by not being able to have a weather tape for the year that the experiment was conducted. However, rough comparisons can be made.

The first comparison on an hourly basis was to see if the trend of the crawl space temperature was the same. The next comparison was to find the point where the outdoor air temperature was the same for both the experimental and analytical cases. The trend of the data between experimental and analytical was consistent; that is, the curves had the same shape and phase. The isolated points of equal outdoor air temperature that were checked were within 1.0 - 1.5C (2-3 F) agreement.

With the crawl space in a free-ventilation mode, the calculation of crawl space temperature was more difficult because of the unknown ventilation rate. This was determined by using a value from ASHRAE of 2.54 l/s per m^2 of floor space (0.5cfm/ft^2) (3). A similar comparison with outdoor air temperature was made with the crawl space in a normal free-ventilating mode. The agreement between the experimental data and the analytical prediction gave the same good relative agreement as for the single-pass crawl space mode of operation and the temperature difference was approximately 1.5 - 2.0C (2-3 F).

Analytically Determined COP and Capacity Increase

By using the single-pass installation, the air temperature over the outdoor heat exchanger is higher than ambient air temperature. This higher air temperature at the outdoor heat exchanger has two effects. Both the COP and capacity of the machine increase as the outdoor heat exchanger air temperature rises. From the analytically generated information produced by computer program CRAWLTEMP, a projected seasonal increase in COP of 0.23 was found and an increase in capacity of 1758 W (6,000 BTU/h) was found. Since the seasonal COP for this heat pump in Oak Ridge is about 2.3, this is a savings of 10% for the five month heating season.

Analytically Determined Additional Heat Losses

As discussed earlier, the predicted crawl space temperature in the single-pass heating mode ran roughly 1.5 - 2.0C (3-4 F) lower than the prediction for the free-ventilating mode causing an additional heat loss through the floor of the thermal envelope on the order of 66 W (225 BTU/h). Additional losses would occur if the water heater were installed in the crawl space. This is caused by the additional temperature difference across the insulation which causes an approximate 5.9 W (20 BTU/h) loss. However, the addition of R-11 insulation wrapped around the water heater reduces this heat loss to an insignificant value (6). Another significant loss would occur if the indoor air handling ducts are the noninsulated type and installed in the crawl space.

Analytically Projected Delay of Supplemental Heat

With the increased capacity of the heat pump due to the outdoor heat exchanger air temperature being higher, the heat pump is now capable of delivering more of the heat the structure requires at lower ambient air temperatures. Effectively, the house machine balance point has been lowered, therefore delaying the operation of the supplemental electric resistance heaters and allowing the heat pump to satisfy more of the load. Based on the monthly analytical predictions, the delay of supplemental heat saves 12% for the five-month heating season.

Experimentally Determined Reduced Defrost

The fourth saving that is not intuitively obvious in this type of installation occurs in the reduced defrost time. This reduction in defrost time occurs because, as the ambient air enters the crawl space, it is warmed up, thereby reducing the relative humidity of the air that reaches the outdoor heat exchanger. With the reduced relative humidity it takes longer for frost to build up on the outdoor heat exchanger. This item saves by keeping the performance and capacity of the heat pump at a higher level for longer periods of time and avoids the use of additional energy for defrosting the outdoor heat exchanger and the implementation of supplemental heat during the period of defrost. This cuts the defrost time for the Oak Ridge area from about 3.5%* to 2%.

The 2% defrost time was determined experimentally by keeping a count of the amount of time that the compressor was running and the amount of compressor run time in the defrost mode. This saves the consumer about 1.5% (based on a 1.5% reduction of a 5-kWh supplemental heater for the average heating load of 5070 W (17,303 BTU/h).

RECIRCULATING CRAWL SPACE AIR-TO AIR HEAT PUMP

A recirculating crawl space heat pump is a proposed installation that has not been tested. In this installation, it would be possible to use either a split unit or a package unit. Due to the lower capital investment, it would be more advantageous to the consumer to use the package unit. In this installation, the normal outside heat exchanger and air handling unit are now recirculating the same air within the sealed crawl space of the structure. An analytical simulation of the installation was made with computer program CRAWLTEMP using the total soil resistance value calculated from the single-pass crawl space heat pump test.

System Configuration

The recirculating crawl space heat pump is a modified installation of the standard split-unit or package-unit system. The only modification is made to the unit is to allow some means of ducting the crawl space air through the outdoor heat exchanger and then recirculating this air within the crawl space. If, in the case of a split package unit, the outdoor package could be installed in an exterior location with adequate ducting provided to allow continual circulation of the air within the crawl space, this would generate a uniform temperature profile within the crawl space keeping in mind the necessity to maintain the manufacturer's specified airflow rate over the outdoor heat exchanger. If the consumer is using a split package unit and the outdoor package is installed within the crawl space, then a minimal amount of ducting would be required to allow for adequate circulation of the air within the crawl space.

In the recirculation crawl space installation it is not only important to seal the crawl space for infiltration of ambient air, but it is also beneficial to seal against moisture. After the heat pump has dehumidified the air in the crawl space, defrost will no longer be needed; therefore, the losses associated with the defrost cycle will be totally eliminated.

Insulation Requirements

As in the single-pass crawl space installation, it is necessary to insulate the floor of the thermal envelope. Although the computer program calculates a higher crawl space temperature than in the single-pass installation, it is still necessary to have the insulation to prevent large heat losses through the floor of the thermal envelope. Insulating water pipes, sewer traps, and water heaters to prevent freezing and additional heat loss, as discussed previously, is also important. It is important to note that any heat loss from the water heater has been neglected since this heat loss is not really lost to the user; it is retained within the crawl space to a higher temperature, then in turn this heat is removed by the heat pump when in operation.

Infiltration Precautions

Infiltration is not a problem in the recirculating installation. When the unit is actively circulating air in the crawl space, it does not reduce the pressure in the crawl space. Hence the driving force for additional infiltration loss is removed.

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*The 3.5% defrost time was extracted from Ref. 7 for a similar unit installed in a conventional manner in Oak Ridge, TN.

Analytical Heating Seasons Predictions

As in the analytical prediction for the single-pass crawl space installation, a heat balance is performed on the air in the crawl space. The heat fluxes through the floor of the thermal envelope, the walls of the crawl space, and the soil are all calculated by the same method using the same material constants. This includes the total resistance value of the soil determined from the single-pass installation test. The difference between the two heat balances is that in the single-pass installation, there is a mass flow that crosses the boundaries of the crawl space; in the recirculating installation, there is no mass flow across the boundaries of the crawl space; however, there is a heat flux associated with the outdoor heat exchanger that is now recirculating the crawl space air.

The heat transfer at the outdoor heat exchanger is calculated by making use of the manufacturer's specified outdoor heat exchanger air temperature vs COP and outdoor heat exchanger air temperature vs capacity. This heat flux is calculated by checking the load of the thermal envelope against the capacity of the machine, based on the past hour's crawl space temperature, and then uses the lowest value as the "load" in the following equation:

$$\text{heat flux} = \frac{\text{load} \times (1.0 - \text{COP})}{\text{COP}}. \qquad (5)$$

The heat flux for the outdoor heat exchanger is then substituted into the energy balance, Eq 3, and a current hour's crawl space temperature is calculated. The heat flux associated with the outdoor heat exchanger is recalculated with the current hour's crawl space temperature. A check of the two heat fluxes is performed. If the check is within 5%, the program continues to the next hour. If the check fails, then the above process is repeated until convergence.

With no experimental data available for this installation, it was impossible to verify any of the generated data.

Analytically Determined COP and Capacity Increase

By using the recirculating installation, the air temperature over the outdoor heat exchanger is higher than ambient air temperature. This higher air temperature at the outdoor heat exchanger has two effects since the COP and the capacity of the machine go up as the outdoor heat exchanger air temperature rises. From the analytically generated information produced by computer program CRAWLTEMP, a projected seasonal increase in COP of 0.27 was found and an increase in capacity of 2100 W (7200 BTU/h). was found. This is a saving of 12% for the five-month heating season, which is passed on to the consumer from the increased COP.

Analytically Determined Decreased Load

In a sealed, vapor-protected crawl space and with recirculating air within the crawl space, the crawl space temperature is able to approach that of the free-ventilated crawl space in a normal heat pump installation, and at times the temperature of the crawl space would exceed that of the conventionally installed heat pump with a free-ventilating crawl space. This condition occurs when the infiltration loss of a crawl space in the free-ventilation mode for a conventionally installed heat pump is higher than the removal of heat from the crawl space in the recirculating crawl space installation. It is predicted that the crawl space temperature will be 0.5 - 1.0C (1 - 2 F) higher on the average for the recirculating installation as compared with a free-ventilating crawl space for the heating season. With a higher crawl space temperature, the heat loss through the floor is decreased by 36.6 W (125 BTU/h). Additional losses to infiltration are nonexistent due to the lack of a negative pressure driving force in the crawl space. The crawl space is now sealed and the heat pump is recirculating the same air within the crawl space.

Analytically Determined Delay of Supplemental Heat

Delaying the need for supplemental heat increases the overall performance of a heat pump by allowing the heat pump to work longer at a higher level of performance. A reduction in supplemental heat was found to save the consumer 15% on the five-month heating bill, based on the monthly analytical predictions of computer program CRAWLTEMP.

Projected Defrost Reduction

In the continuous installation, the outdoor heat exchanger acts as an enormous dehumidifier. After a very short period of time, the crawl space will become dehumidified to the point that the defrost cycle should not even occur unless an enormous amount of water was added to the crawl space by some external source. This would indicate a very significant saving by reducing the defrost time from around 3.5% of the compressor run time to almost 0% of compressor run time. This saves not only the additional energy expended to defrost the outdoor heat exchanger, but it also eliminates the need for supplemental heat for the period of defrost. With the crawl space sealed and the outdoor heat exchanger acting as a dehumidifier, the problem of a humid or damp crawl space causing deterioration of the structure is nonexistent. Based on a 3.5% reduction of a 5-kWh supplemental heater, this saves the consumer about 3.5% of the average load of a 5070 W (17,303 BTU/h).

CONCLUSIONS

The single-pass crawl space installation was experimentally investigated, whereas the recirculating crawl space installation was analytically investigated based on the data collected from the single- pass installation.

The single-pass and recirculating crawl space installations showed savings in three areas. These three areas are the increase of COP and capacity of the machine; the delay and deletion of the need for increasing the capacity of the heat pump by implementing electrical resistance heaters; and the delay or deletion of the requirement to defrost the outdoor heat exchanger. There are losses due to this type of installation in the form of heat losses through the floor of the thermal envelope. A breakdown of these savings and losses, based on the analytical prediction and checked, when possible, by experimental data, for the single-pass installation and a five-month heating bill in Oak Ridge, TN, is as follows: The increased COP saves the consumer 10%; the increased losses through the thermal envelope costs the consumer 1%; the delay of supplemental heat due to increased capacity saves the consumer 12%; and the reduced defrost saves the consumer 1.5%. Totaling all percentages, the consumer saves a net amount of 22.5%.

A similar breakdown of the savings and losses for the recirculating installation based on the analytical prediction with no experimental data available to check results, for a five-month heating bill is as follows: The increased COP saves the consumer 12%; the decreased losses through the thermal envelope saves the consumer 1%; the delay of supplemental heat due to increased capacity saves the consumer 15%; and the reduced defrost save the consumer 3.5%. Totaling all percentages, the consumer saves a net amount of 31.5%. With regard to these crawl space installations, it is very important that the floor of the thermal envelope be well insulated; that all piping be protected from freezing; and, in the event that the water heater is installed in the crawl space, additional insulation be applied to the water heater. It is also very important for the single-pass installation that the holes in the floor of the thermal envelope be plugged to prevent any additional infiltration loss, and it is imperative that the airflow over the outdoor heat exchanger remain as close to the manufacturer's specifications as possible. In some cases this may require an additional hole in the crawl space for inlet air on the opposite end of the structure. The defrost condensate should be piped outside, and the warm air vapor should be removed by a small exhaust fan to prevent structural damage.

FUTURE WORK

The house described above, and three other houses in the Knoxville-Oak Ridge area with crawl space heat pumps, are currently being monitored by both The University of Tennessee and the Oak Ridge National Laboratory. In addition, the analytical techniques above are being refined, particularly in regard to the calculation of the heat transfer from the soil, so that the performance of the crawl space installations can be predicted for other geographical areas and soil types. These results will be reported at a later date.

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TABLE 1
Soil Temperatures

1977 Julian day	Experimental Data In crawl space C (F)	Experimental Data Outside C (F)	Analytical approximation C (F)
15	6.1 (43)	7.2 (45)	6.7 (44)
45	5.6 (42)	6.1 (43)	6.1 (43)
75	6.7 (44)	7.2 (45)	7.8 (46)
315	12.8 (55)	13.3 (56)	12.2 (54)
345	8.3 (47)	9.4 (49)	8.9 (48)

TABLE 2
Results Generated by Program Crawltemp[a]

	Mode*	Jan.	Feb.	Mar.	Nov.	Dec.
Heat flux through crawl space wall (W)	1	-1665	-1656	-956	-967	-1464
	2	-1461	-1442	-816	-824	-1264
	3	-1811	-1800	-1004	-1052	-1591
Heat flux through floor of thermal envelope (W)	1	708	715	575	401	597
	2	764	774	614	441	563
	3	668	675	562	378	562
Heat flux from soil (W)	1	6742	6649	3584	3731	5845
	2	9255	9280	5309	5499	8335
	3	4947	4867	2995	2683	4288
Heat flux airflow through crawl space or heat removed from crawl space (W)	1	-5785	-5709	-3202	-3165	-4978
	2	-8559	-8612	-5106	-5116	-7726
	3	-3804	-3742	-2553	-2009	-3259
Supplemental heat required (W)	1	1906	1740	273	4	1032
	2	535	443	26	0	194
	3	301	237	5	0	62
Temperature of crawl space air (C)	1	2.2	2.2	6.1	10.0	5.0
	2	1.1	0.6	5.0	9.4	3.9
	3	3.3	2.8	6.1	11.1	6.1
Outside air temperature (C)		-10.0	-10.0	-1.1	-3.3	-5.6
Heating load (W)		6297	6120	4165	3299	5512

[a]Values are monthly averages.

*"Mode" refers to the type of heat pump installation. Mode 1 is the conventional heat pump installation with free ventilation of 2.54 l/s per m^2 of floor space (0.5 cfm/ft^2). Mode 2 is a single-pass crawlspace installation. Mode 3 is a recirculating crawlspace installation.

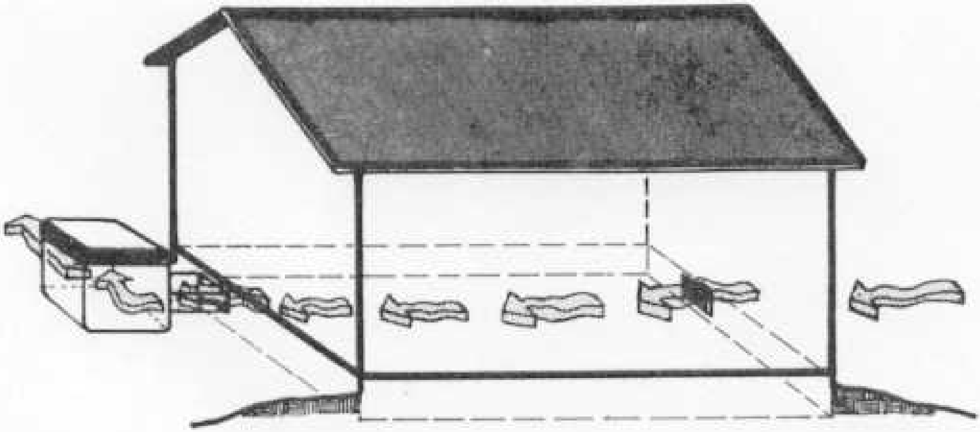
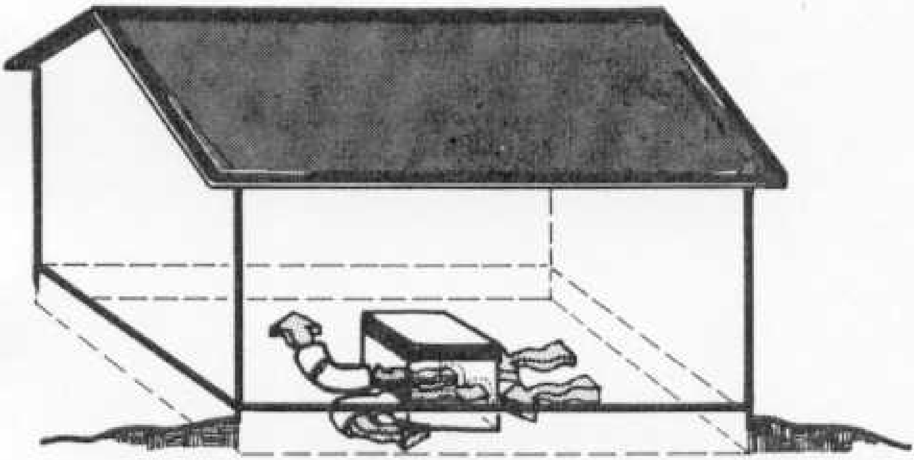
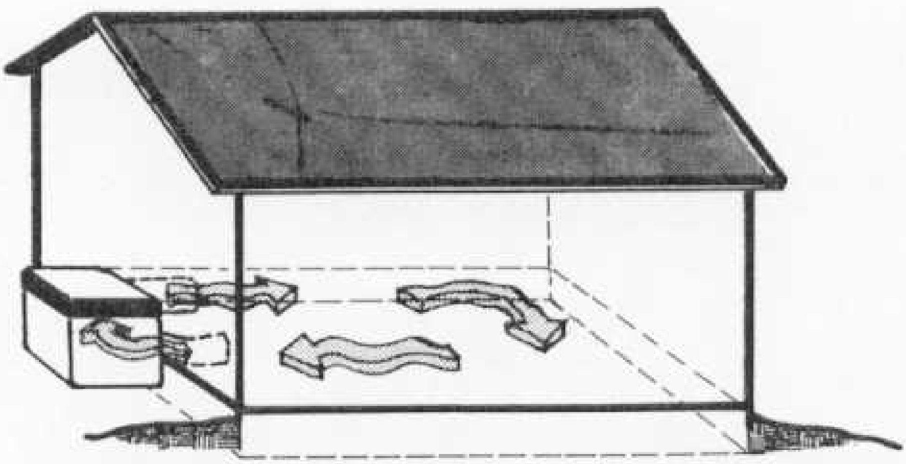


Fig. 1 Single-pass air-to-air ground coupled (crawl space) heat pump



(a) Heat exchanger in crawl space



(b) Heat exchanger external to crawl space

Fig. 2(a,b) Recirculating air-to-air ground coupled (crawl space) heat pump

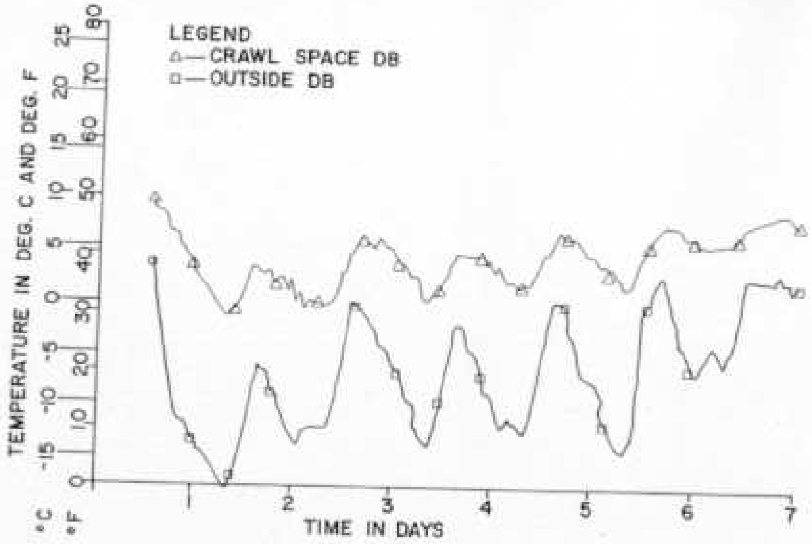


Fig. 3 Single-pass crawl space operating mode, temperature data, starting date January 28, 1977

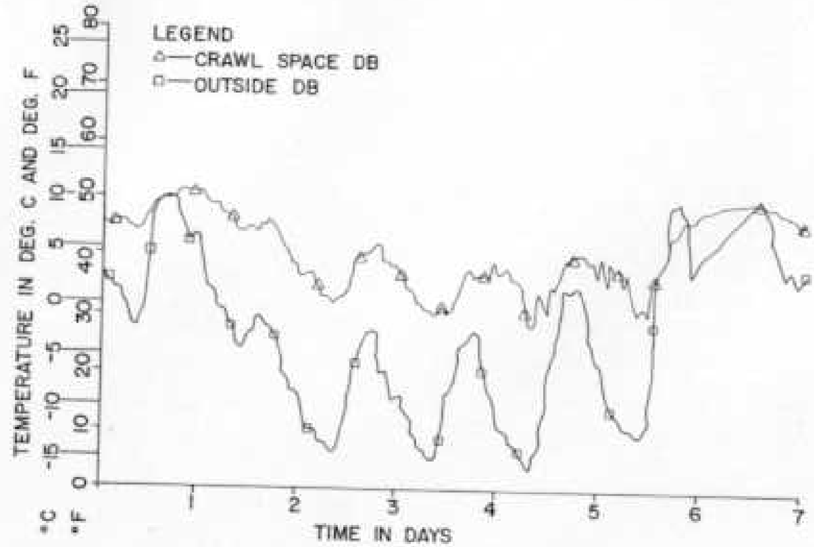


Fig. 4 Single-pass crawl space operating mode, temperature data, starting date February 4, 1977

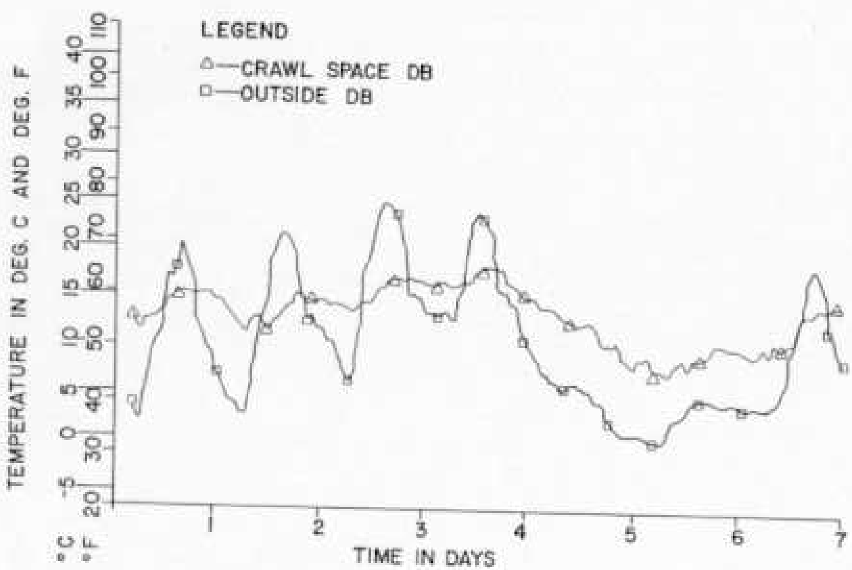


Fig. 5 Single-pass crawl space operating mode, temperature data, starting date March 22, 1978

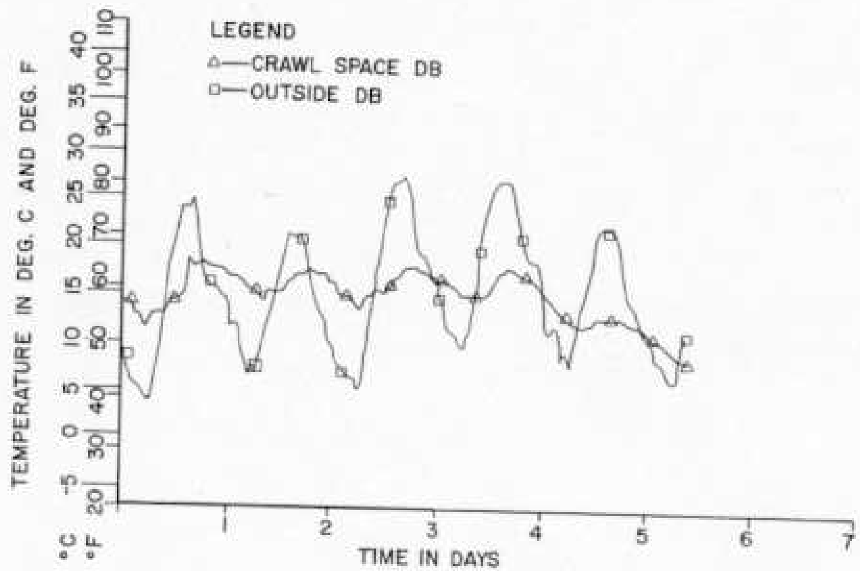


Fig. 6 Single-pass crawl space operating mode, temperature data, starting date March 29, 1978

DISCUSSION

J. LAWSON, Commercial and Industrial Eng., TN Valley Authority, Cleveland: How does the climate affect the amount of savings realized?

L. REID: The purchased energy for heating with the crawl space heat pump installation should be less than with a conventional installation for all climates, but the magnitude of this decrease is unknown. The performance in different climatic locations cannot be predicted with the computer program developed in this study, since the heat transfer from the ground was derived from the experimental data and not from fundamental soil properties. In work currently in progress, the soil heat transfer is being calculated from soil properties and includes the effect of water migration and heat conduction. Parametric studies will then be made for different soils in various climatic regions.

J.L. HELDENBRAND, Res. Coordinator, Energy Conservation in Buildings, National Bureau of Standards: Have you considered the cost of any added insulation that might be required in the floor, or accounted for the penalty of added heat exchange through the floor due to the h.p. installation in the crawl space?

REID: With today's standards for energy conservation, it would be good practice and cost effective to insulate beneath the floor even without the crawl space heat pump installation. The extra heat loss to the crawl space for the single pass mode was only 1%, and this was considered in calculating the net savings. For the recirculating mode with the heat exchanger in the crawl space, it is predicted that the crawl space would be at or above its normal temperature, so that the heat loss to the crawl space would actually decrease, saving 1% energy usage.