AN INTEGRATED APPROACH TO ENERGY-CONSERVING HOUSE DESIGN: A REPORT ON THE FIRST YEAR OF OCCUPANCY

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ABSTRACT

A house was built to an integrated low-energy design philosophy by a site crew with no special training nor experience in low energy house construction. It has performed up to and beyond expectations in all respects. By virtue of an air management philosophy that complements the physics of the envelope, the system was intended to be much more forgiving of construction imperfections than low-energy house techniques to date, while maintaining an environment ideal for both occupants and structure.

Since control of moisture movement into the wall cavity is achieved by the air management system, a vapor barrier is not required, permitting the easy adaptation of the system to cooling-dominated climates. The system acknowledges the benefit of superinsulated walls in eliminating the local cold spots heating systems have traditionally been designed to overwhelm. The simplifications this permits, combined with less stringent requirements for airtightness, offer cost savings compared with other low energy house building techniques. An air-to-water heat pump offers effective ventilation heat recovery and background dehumidification and cooling.

INTRODUCTION

At the time (1982) that work started on the system described below (subsequently referred to as the F.C.I. system), it was widely felt that superinsulation as a technique for conserving space heating energy had been taken to its logical limit. The focus of attention shifted to air movement through the house: the energy needed to heat this air could amount to 50% or more of the space heating requirement of a superinsulated house.

A fledgling industry developed, selling air-to-air heat exchangers, devices using principles that had been employed in manufacturing industries for many years. These units rely on the exchange of heat between outgoing warm air and incoming cool air, and a requirement for their effective performance as a part of the house energy system was that as little as possible of the air moving through the house should bypass them.

Speaking generally, the most consistent cause of bypassing would be the stack effect, where the heated house acts as a chimney, drawing cold air in through the leaks at the bottom of the house, discharging heated air through leaks at the top of the house. In order to reduce this cause of inefficiency, and partly because of worries about the exfiltrating warm air causing condensation in the wall cavity, it became an article of faith that the house should be as airtight as possible. It is relatively simple to tighten a house to about 2.5 air changes per hour at 0.2 in w.c. (50 Pa) depressurization. To reduce this figure significantly requires a much more rigorous approach to the construction of the envelope.

Many approaches to the problem came on to the scene, with various advantages and disadvantages. All, however, accepted that a substantial measure of experience in the

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technique was needed to avoid a significant cost premium in the building of a house. Our experience was that many builders were reluctant to enter into this learning experience. In addition, many were disheartened by the lack of a design package with clear and simple rules to follow. Those promoting low energy houses were reluctant to be too prescriptive, perhaps in the belief that this would offend the "free spirit" of the typical builder. What appeared to happen was that many interested builders took the lack of specifics as an indication of uncertainty and stayed away from low energy houses. As a result, the movement toward increasing the proportion of houses superior in every respect to the conventional appeared to be stalling.

THE F.C.I. SYSTEM

Sweeping aside the "add-on" approach to building low-energy houses allowed us to examine the physics of the house operating as a system, acknowledging the interaction of envelope design, air management, heat recovery, and heating/cooling system.

The decision was made to use an exhaust-only ventilating system designed to give 0.5 air changes per hour, with heat pump heat recovery. This approximately duplicates the winter pressure profile of a house with a flue, whereby the flue depressurizes the house because of stack effect, to the point where the neutral pressure plane lies above the ceiling, eliminating the condensation risks associated with exfiltrating moist air.

Our initial design target was to depressurize by approximately 0.04 in w.c. (10 Pa), this corresponding to the stack effect differential pressure at 68 F (20°C) indoor temperature, -4 F (-20°C) outdoor temperature.

Assuming a laminar flow regime for the air flowing into the house, this would require a house with a test characteristic of 2.5 air changes per hour at 50 Pascal depressurisation. In fact, our test house had a characteristic of 2.1 air changes per hour at 0.2 in w.c. (50 Pa), and a flow exponent given by

$V \propto P^{0.835}$ where V = airflow volume
P = pressure difference driving flow

thus, the depressurization indicated at 0.5 air changes per hour is about 0.035 in w.c. (9 Pa).

The relatively high exponent (0.7 to 0.75 would be more usual) is most likely due to the airtightening techniques used. Note that the higher the exponent, the better the air barrier effect at normal operating pressure differentials, as opposed to the relatively high figure of 0.2 in w.c. (50 Pa) used for testing.

Our aim was a simple system, capable of implementation by regular site crews, leading to an airtightness characteristic of between two and three air changes per hour at 0.2 in w.c. (50 Pa). Experience suggests that this region is easily reached, but a significant reduction in leakage rate (down to 1.5 air changes per hour or less) requires at least twice as much effort. We were therefore comfortable with the idea of designing for all of the incoming fresh air to flow through the envelope. In the event that a very tight house was built, provision for a fresh air intake could easily be made and the house "tuned" to give the depressurization required.

The advantages offered by drawing air in through the envelope are:

1. Inward movement of dry winter air has a dehumidifying effect on the structural lumber, i.e., no vapour barrier is required.

2. A major first step in evenly distributing fresh air through the house has been taken.

Tightening the Envelope

In order to attain airtightness in the region of two to three air changes at 0.2 in w.c. (50 Pa), there are three major steps:

1. Seal the major and obvious leak points:

- sill plate and header areas (See Figure 1)
- utility penetrations
- plumbing stacks
- windows

The sill plate requires a thick, soft gasket between it and the foundation top (thin gaskets will conform to only the slightest irregularities).
Headers should be wrapped with an air retarding breather-type plastic-spun bonded polyolefin. Ordinary polyethylene has the potential for trapping moisture transmitted along joists.

Utility penetrations may be caulked or taped using contractors' tape.

Plumbing stacks require a neoprene boot-chimney flashing; boots or homemade cutouts from neoprene sheet are fine.

Windows may be sealed by using a polyethylene skirt around the frame, taped to the exterior air barrier, or, if the exterior sheathing is resilient, the brick mould may be used to trap the sheathing (as a gasket) with a bead of caulking to enhance the seal.

2. Cover the outside walls with a vapor-breathing air retarder.

The recommended material for this duty is a spun bonded polyolefin. In our case, this material was integral with the medium density glass fiber sheathing, the joints being sealed by means of a contractors' sheathing tape.

Using a glass fiber external sheathing in this way serves to move the condensation plane outwards, away from the structural lumber.

The spun bonded polyolefin has a high resistance to airflow, and, combined with the moderately dense glass fiber matrix of sheathing, probably accounts for the higher flow exponent than that normally found.

3. Modify the framing and drywall technique slightly to make better use of the drywall's airtightness.

The objective is to make the exterior drywall as continuous as possible. This is achieved by leaving the outermost stud of partition walls an inch clear of the exterior walls, permitting a continuous run of drywall behind the partition wall.

Similarly, one should avoid bulkheads that connect with the outer framing: these should stop short of the exterior wall, ideally being built in after initial drywalling is complete.

Needless to say, low energy performance requires lots of insulation. The test house was designed to meet the budget of the R2000 program for the Toronto climate, and the insulation levels were chosen accordingly:

basement	-	R12 (RSI 2.11) exterior glass fiber insulation
walls	-	2 x R12 (RSI 2.11) batts + R6.7 (RSI 1.18) exterior sheathing
attic	-	R35 (RSI 6.16) batts + R12 (RSI 2.11) batts (crossed) (See Figure 1)

The header area is one that causes some headaches for low energy house builders. Negative pressure ventilation goes a long way to eliminating the worries previously expressed about condensation in this tricky area.

Complementary features are the vapour permeable wrap on the outside and the insulation "pillows" on the inside. These pillows are simply polyethylene bags stuffed with glass fibre batts to form a snug fit in the joist spaces.

Air Management and Heat Recovery

Ventilation of the house is provided by exhausting 0.5 air changes per hour via the wet rooms (bathrooms, laundry, and kitchen [Figures 2 and 3]).

The ducting for this takes the form of 3 in (76 mm) diameter galvanized steel, located in interior partition walls and generally dropping straight down to the basement/utility area.

This exhaust induces an inward flow of fresh air through the walls. Even distribution of this incoming air was the aim of the system, and the polyolefin "skin" outside the framing serves to provide this. The eventual points of ingress to the living space are the electrical receptacles and inevitable imperfections in the drywall seal.

Note that the channeling of air that has been forced to follow a tortuous path through a substantial mass of fibrous insulation is quite different from the usual experience of cold drafts from leaky receptacles in a conventional house. In the former case, the air is tempered on its long journey through a warm cavity; in the latter, the receptacle represents one end of a short path from a major leak in the outer skin. (The occupants of the test house have commented on the absence of cold drafts as being a major improvement on their previous, conventional, house, the houses being superficially similar and of recent construction).

This ventilation approach should, on its own, provide a substantially better environment than the conventional home experiences.

As a supplement to this means of creating air movement through the dwelling space, a recirculation loop was installed, with the emphasis on simplicity. This loop, in winter, extracts air via high wall grilles in the bedrooms and returns it to the main floor via a floor register, or registers.

Heat recovery from the exhaust stale air is achieved by means of a hot water heat pump. This unit cools the stale air from room temperature to about 39 F (4°C) before it is discharged to outside.

The heat extracted is pumped into the self-contained 60 gallon U.S.(227 L) domestic hot water tank. If the house is calling for heat and the demand for domestic hot water has been satisfied, a pump circulates hot water through a finned-tube coil mounted in the air recirculation loop.

In summer, the airflows are interchanged by means of a simple ductwork switching device. Air is now drawn into the recirculation loop via the floor register or registers and delivered to the high wall grilles in the bedrooms. On its way, it passes through the evaporator coil of the heat pump and is cooled and dehumidified. At present, the cooling/dehumidification capacity is a modest 6500 BTU/h (1900 W), but it is planned to increase this capacity on units to be used in cooling dominated climates.

The path for stale air in the summer is now via the hot water coil. If the house is calling for cooling and the domestic hot water demand has been met, hot water is pumped to the hot water coil and this heat is rejected to outside.

It will be apparent that this system may be operated in a pressurizing mode during the cooling season, if so desired. This has the effect of opposing inward migration of warm, humid air and the condensation associated with it.

This easy adaptation from cold climate to warm climate design makes the system unusual in the low energy house field.

Heating System

In areas where the demand for heat will exceed the 7500 Btu/h (2200 W) output of the heat pump, some backup heating will be required.

The most economical means of providing backup in the test house was electric baseboard heaters, but this will vary from place to place.

With the advent of economical balanced flue gas convector heaters, it may well be that a couple of these units strategically located in the house will provide all the needed backup heat.

The recommended mode of operation for the heating system is to use a two-stage thermostat: the first stage of heating would be provided by the heat pump; the second by the backup heating, if the thermostat sensed the need for it.

A fireplace was a standard feature of all the houses in the subdivision where our test house was located. Although it made no sense from an economics point of view, it was regarded by the builder as an essential sales attraction.

We specified that the fireplace should be a zero clearance type, with airtight doors and external air supply. In addition, the chimney was an insulated steel type, running inside the insulating envelope.
These features ensure that the fireplace enjoys a draft advantage over the house interior until the flue temperature is below about 120 F (50°C).

Monitoring Procedure

Our main areas of interest in the house were:

- Total energy consumption
- Wall moisture content
- Air quality

Total Energy Consumption

The total energy consumption of the house was ascertained by reading the electricity meter for the first year of occupancy.

The occupants were a two adult, two small children family, who were given no special operating instructions. In fact, they were told to do whatever came naturally, including opening windows, turning on local backup heat if they felt cool, etc.

A short-term indication of the house performance was obtained just prior to occupancy by taking readings over two nights in winter during a period of heavy cloud.

Wall Moisture Content

When construction of the house was complete, two access hatches were placed in the drywall, one in a ground-floor laundry at the bottom of the wall, one in a second-floor bathroom at the top of a wall. These hatches were almost in line vertically on a shaded west wall (see Figure 4).

The moisture content of the outer stud was measured by a conductivity-type pin probe. A reading was also taken from the inside of the ground-floor header on the west wall.

Air Quality

Shortly after completion, but before occupancy, formaldehyde readings were taken. A similar conventional home was tested.

Radon readings were taken using track-etch cups in both the test house and a conventional house of similar construction.

RESULTS

Total Energy Consumption

Total energy consumption for the house during the period March 12, 1984, to March 13, 1985, was 16222 kWh. To obtain a close estimate of effective space heating energy consumed, subtract 5110 kWh for water heating*
and 5110 kWh for appliances.*

The family occupying the house did not own an electric clothes dryer, so an amount of 2 kWh/day was added.

The effective space heating cost was estimated at:

16222 - 5110 - 5110 + 730 = 6732 kWh/year.

*Canadian average

(Note that the effective space heating cost includes a credit that results from lower domestic hot water costs outside the heating season).

Total house area = 3000 ft^2 (279 m^2)

Toronto heating requirements are 7348 Fahrenheit degree-days

(4082 Kelvin degree-days)

Short-Term Energy Demand

The overnight demand during two nights separated by a day of heavy cloud cover averaged 13000 Btu/h (3.8 kW).

The outside temperature varied between 0 F (-18°C) and -4 F (-20°C) with little wind

Inside temperature was maintained at 68 F (20°C) above grade and 64 F (18°C) in the basement.

No window drapes were in place.

Wall Moisture Content (See Table 1).

Air Quality (See Tables 2 and 3).

DISCUSSION OF RESULTS

Total Energy Consumption

The HOTCAN prediction (Appendix A) for this house as built, giving an arbitrary credit for 70% heat recovery on 0.5 air changes per hour, was:

19933 kWh/year total energy consumption. This was made up as follows:

Space Heating:	9713 kWh/year
Domestic Hot Water:	5110
Appliance Useage:	5110
	19933 kWh/year

The actual total consumption (16222 kWh/year) and derived space heating consumption (6732 kWh/year), both compare favorably with the HOTCAN prediction.

HOTCAN's record as a predictor of low energy house performance has been reasonably good, with a tendency to predict about 10% low on average.

As a reference base, a superficially similar house built to the requirements of the Ontario Building Code would have a total energy consumption of about 39000 kWh/year, assuming it operated with the prescribed ventilation rate of 0.5 air changes per hour (Appendix B).

Bearing in mind the house was drying out, imposing extra load on the heating system, and the use of summer cooling for 24 hours a day (i.e., pumping more heat than could be recovered in domestic hot water heating), the house performed very well in terms of energy consumption.

Short-Term Energy Demand

The HOTCAN figure for the design heatload at 1 F (-17.2°C) ambient temperature for the test house was 5.36 kW, assuming 70% recovery of the air change heat loss and 70 F (21°C) indoor temperature.

Again, the actual test house number (3.8 kW average) compares favorably with the prediction.

Wall Moisture Content

The values recorded are encouraging both in magnitude and stability. The Toronto climate varies from bone dry air in midwinter to almost saturated high temperature air in summer.

The structural lumber appears to exist in an environment leading to maximum longevity and minimum cycling.

Air Quality

Formaldehyde. The level of formaldehyde is reasonably low (0.01 parts per million is a recommended maximum)

An average amount of formaldehyde-generating material was used in the house in such items as chipboard furniture in kitchen and bathrooms and carpeting throughout the house.

Radon. The results suggest that radon levels are below the EPA suggested limit of three picocuries per litre.

Comparison with the conventional house indicates no significant change in level created by the ventilation mode.

This is in keeping with a major school of thought, which argues that location is the overwhelming factor in determining radon concentration.

If this is the case, two approaches to the problem are suggested: (1) seal the interior of the basement by capping drains and using impervious paint and (2) isolate the below grade space from the above-grade space and use a branch of the air recirculation loop to pressurize the below grade space.

GENERAL

The incremental cost for this system over a conventional tract house in Ontario was estimated by the builder as being $5600 Canadian on a routine basis.

At an annual saving of $1000 Canadian (at 4.3 cents/kWh), this gives a simple payback of 5.6 years, assuming no tax relief. Perhaps more significantly, the first year monthly payments of mortgage plus energy would total less than that for a standard house, to acquire a more valuable property.

A considerable amount of interest has been expressed by electrical utility companies in the potential for peak shaving.

If a standard hot water tank were connected in parallel with the tank incorporated in the heat pump unit, the stored heat, combined with the heat pumped by the compressor (consuming about one kilowatt), would be sufficient to hold the temperature of the low energy house relatively steady over a three hour peak.

CONCLUSION

1. The integrated house design offers a relatively simple and attractive way of reducing effective space heating energy usage by 70% to 80% of that of a house built to Ontario Building Code Standards, each house having a recommended ventilation rate of 0.5 air changes per hour.

2. An environment conducive to good lumber performance in the walls has been created without relying on a meticulously installed vapour retarder.

3. The occupants of the first house using the system are particularly happy with the economy, comfort, quiet, and freshness of the house.

ACKNOWLEDGMENT

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APPENDIX A

PROGRAM HOTCAN

FCI is
Toronto

Design heat loss at -17.2°C = 5.36 KW
Temperatures (°C) Main Floor = 21 Basement = 20
Sensible heat gain from people (kWh/D) = 0
Daily base electric consumption (kWh/D) = 14
Daily hot water energy consumption (kWh/D) = 14
Mass level chosen is <A>
Window shading coefficients : South = .72 North = .72
East = .72 West = .72
South overhang geometry: Average window height = 1.52 M
Average overhang width = .61 M
Average height above window = .2 M
Natural infiltration rate (AC/HR) = 0
Forced ventilation rate (AC/HR) = .5
Heat recovery effectiveness on ventilation air = 70%

Monthly Summary of Energy Consumption

Month	Thermal Load kWh/D	Monthly Solar Frac	Aux.Heat Req. kWh/D	Tot.Cons. kWh/D
Jan.	81.91	.21	64.39	92.39
Feb.	81.61	.25	61.21	89.21
Mar.	67.51	.29	47.85	75.85
Apr.	45.23	.38	28.08	56.08
May	25.93	.61	10.19	38.19
Jun.	6.09	1	0	28
Jul.	0	1	0	28
Aug.	0	1	0	28
Sep.	9.94	.86	1.38	29.38
Oct.	28.48	.56	12.42	40.42
Nov.	49.38	.24	37.5	65.5
Dec.	71.63	.18	58.4	86.4

Estimated annual space heating 34.97 GJ, or 9713.32 kWh.
Annual solar fraction = .31

Annual Predicted Fuel Costs

Fuel costs are for Toronto as of April '83.

Energy Source	Cost Per Unit	Space Heating	Hot Water	Lights and Appliances
Electricity	$.043/kWh	$417.67/YR	$219.73/YR	$219.73/YR

APPENDIX B

PROGRAM HOTCAN

Ont Building Code
Toronto

Design heat loss at -17.2°C = 11.5 KW
Temperatures (°C) Main Floor = 21 Basement = 20
Sensible heat gain from people (kWh/D) = 0
Daily base electric consumption (kWh/D) = 14
Daily hot water energy consumption (kWh/D) = 14
Mass level chosen is <A>
Window shading coefficients : South = .83 North = .83
East = .83 West = .83
South overhang geometry: Average window height = 1.52 M
Average overhang width = .61 M
Average height above window = .2 M
Natural infiltration rate (AC/HR) = .5
Forced ventilation rate (AC/HR) = 0

Monthly Summary of Energy Consumption

Month	Thermal Load kWh/D	Monthly Solar Frac	Aux.Heat Req. kWh/D	Tot.Cons. kWh/D
Jan.	193.31	.11	172.88	200.88
Feb.	192.38	.13	167	195
Mar.	160.77	.16	135.62	163.62
Apr.	111.05	.2	88.64	116.64
May	68.2	.28	49.18	77.18
Jun.	6.09	1	0	37.54
Jul.	3.4	1	0	28
Aug.	5.53	1	0	28
Sep.	33.55	.5	16.76	44.76
Oct.	74.88	.26	55.63	83.63
Nov.	121.32	.11	107.41	135.41
Dec.	170.7	.09	155.44	183.44

Estimated annual space heating 104.32 GJ, or 28978 kWh.
Annual solar fraction = .17

Annual Predicted Fuel Costs

Fuel costs are for Toronto as of April '83.

Energy Source	Cost Per Unit	Space Heating	Hot Water	Lights and Appliances
Electricity	$.043/kWh	$1246.05/YR	$219.73/YR	$219.73/YR

TABLE 1

Percentage Moisture Content of Lumber

Date	Header	Laundry Room		Bathroom	
	H	O	I	O	I
March 7, 1984	13.5	13.6	11.2	12.6	9.6
March 14, 1984	16.0	15.0	13.0	12.5	9.5
May 22, 1984	13.5	13.5	11.0	12.5	10.0
August 30, 1984	17.0	13.0	13.5	12.0	12.0
November 8, 1984	13.0	12.5	12.0	13.5	13.0
January 3, 1985	13.0	12.5	12.0	12.5	11.0
January 23, 1985	13.5	11.5	11.0	11.0	10.0
March 13, 1985	14.5	12.75	12.5	11.0	10.0

TABLE 2

Formaldehyde

	Formaldehyde (parts per million)	
	F.C.I. Test House	Conventional House
Dining Room	0.004	0.004
Master Bedroom	0.003	0.003

3 hour average using NIOSH P&CAM 125 method.

TABLE 3

Radon

	Radon pCi/l	
	F.C.I. Test House	Conventional House
Basement #1	1.70	1.44
Basement #2	2.24	1.97
Family Room	0.50	1.03
Living Room	1.03	0.63
Upstairs	0.63	1.17
Average	1.22	1.25

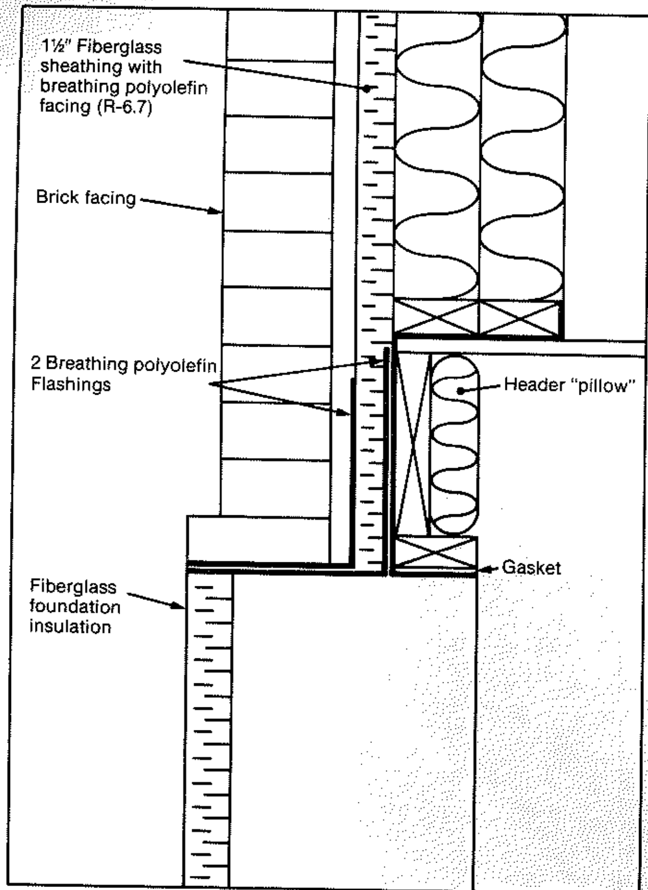

Figure 1. Sealing in header area

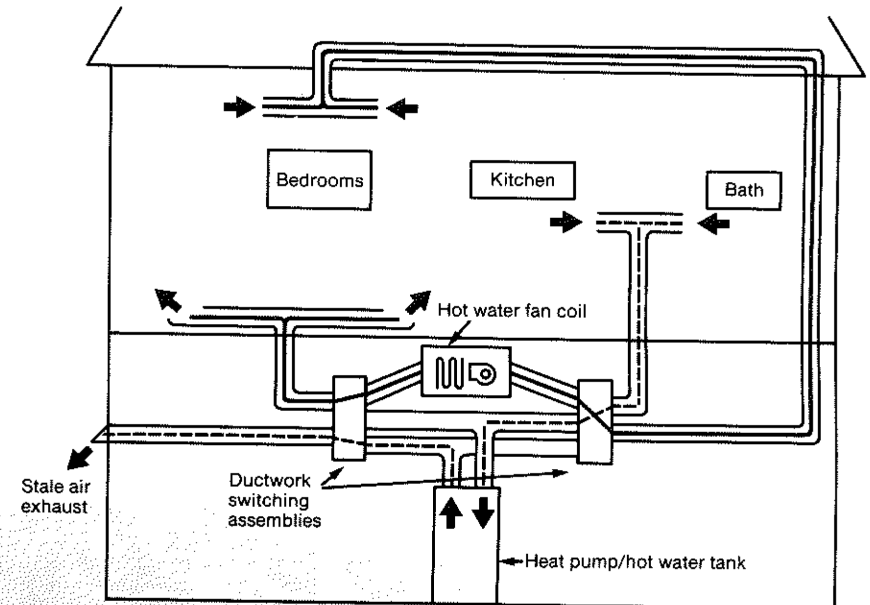

Figure 2. Air management system in winter mode. Heat is taken from air exhausted from wet rooms. Recirculating house air is heated by fan coil unit. (Switching assemblies and fan coil unit are combined in one box.)

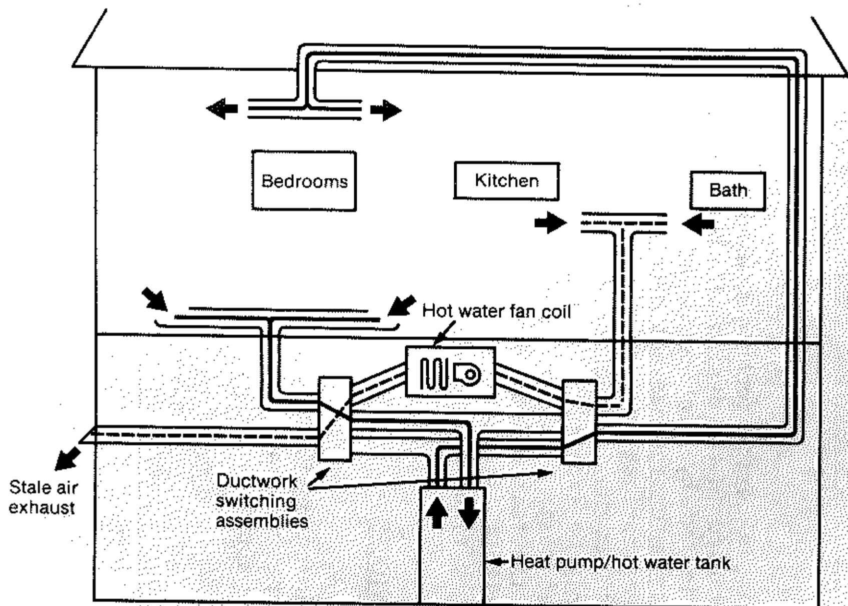

Figure 3. Air management system in summer mode. Recirculating house air is cooled by heat pump. Air is exhausted from wet rooms by fan coil unit. Excess heat from heat pump is transferred into exhaust air at fan coil unit. (Switching assemblies and fan coil unit are combined in one box.)

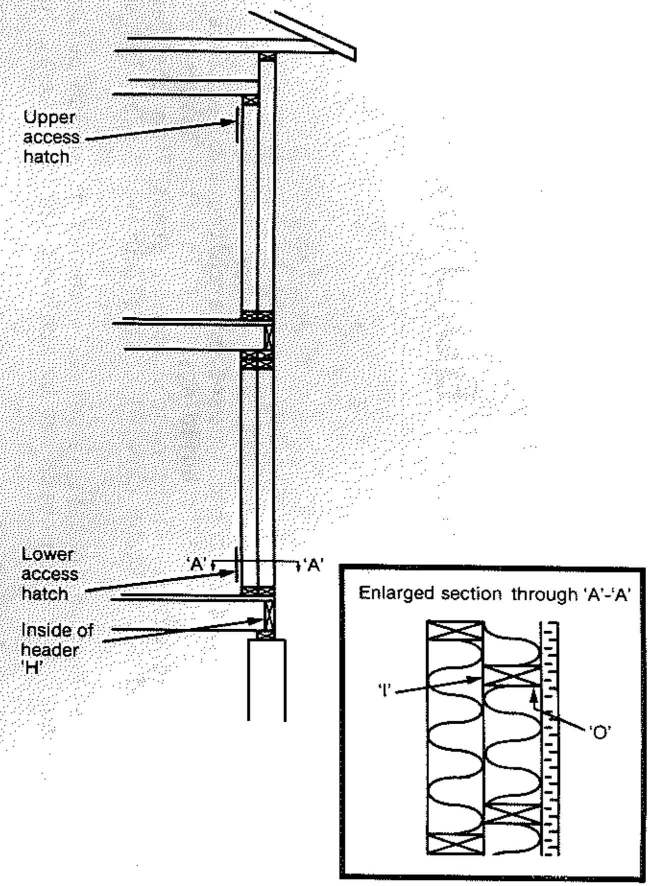

Figure 4. Location of access hatches and test points for wall moisture readings. (Construction details omitted for clarity.)