ISSN 0701-5216

BUILDING PRACTICE NOTE

MARK XI ENERGY RESEARCH PROJECT SUMMARY OF RESULTS, 1978-1981

by

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Ottawa, January 1982

National Research Council Canada
Conseil national de recherches Canada

NO. 27

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INTRODUCTION

The Housing and Urban Development Association of Canada (HUDAC) and the Division of Building Research (DBR) have been cooperating on a project to study energy use in four single-family detached houses built in Orleans, Ontario, 5 kilometres east of Ottawa in 1977. These houses were designated the HUDAC Mark XI Project.

The objectives of the project include the following:

(1) to demonstrate the energy saving resulting from upgrading the thermal resistance and air-tightness of the building envelope;

(2) to study the potential problems associated with thermal upgrading;

(3) to determine the thermal performance of space-heating systems (gas furnace, air-source heat pump, and solar);

(4) to determine the heat loss through different sections of the houses;

(5) to determine the accuracy of mathematical models in predicting energy consumption in houses;

(6) to determine the effect of occupancy on the energy usage in houses.

DESCRIPTION OF THE MARK XI HOUSES

The four detached two-storey, single-family test houses are located on adjacent lots in a housing development near Ottawa (Figure 1). Each has 118 m^2 (1249 ft^2) of living area and a full basement with cast-in-place concrete foundation. The interior dimensions and interior finishes are identical in all four houses (Figure 2); the exterior finishes are nearly identical. References (1) and (2) give full details.

House 1 (H1) was built according to the insulation requirements of the 1975 Ontario Building Code. Houses 2, 3 and 4 (H2, H3 and H4) were constructed with increased levels of insulation, triple-glazed windows and special features to increase air-tightness. The nominal thermal characteristics of the main components of the houses are given in Table 1, and a more complete description is available in Reference (1); the R-values given refer to the insulation installed in the houses.

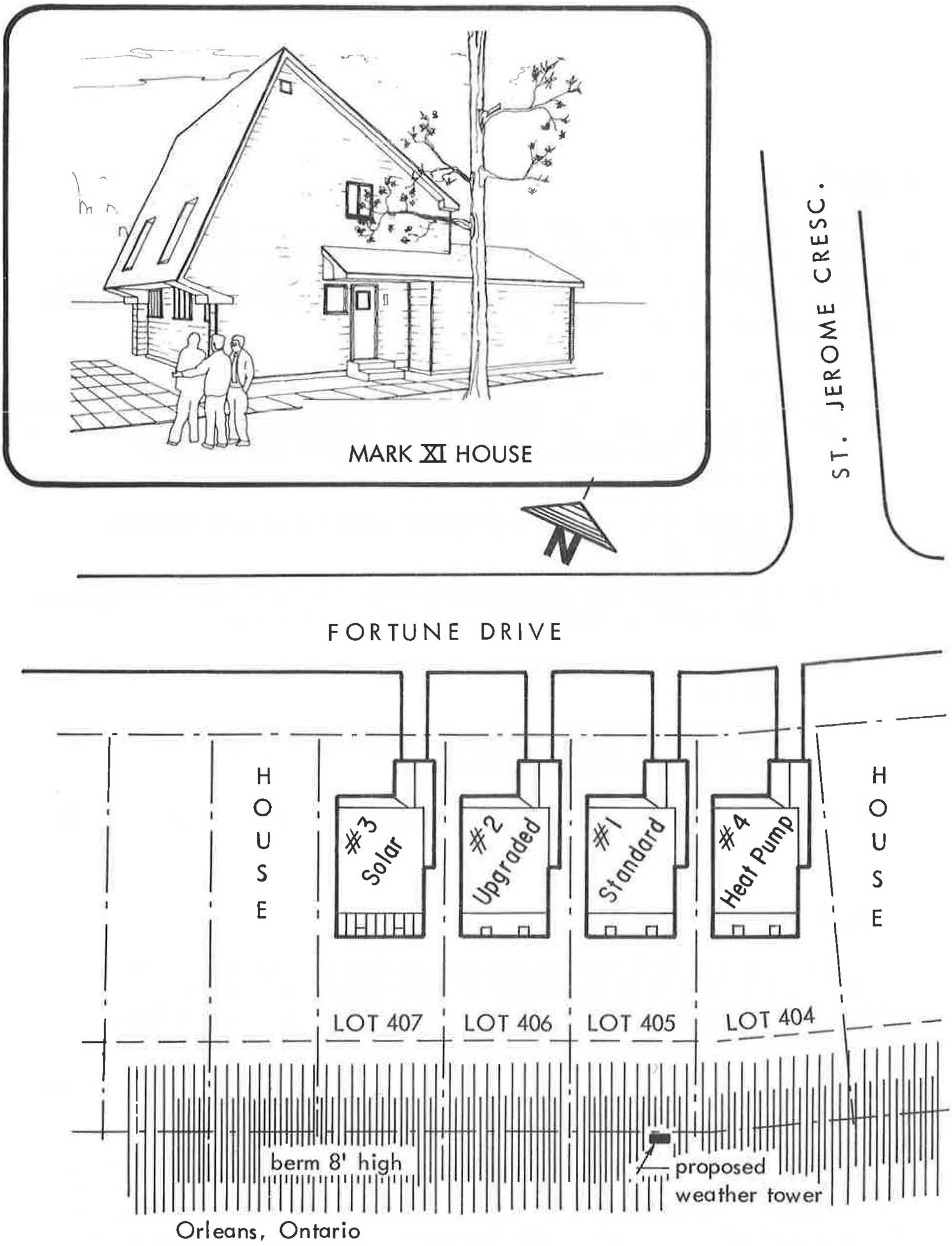
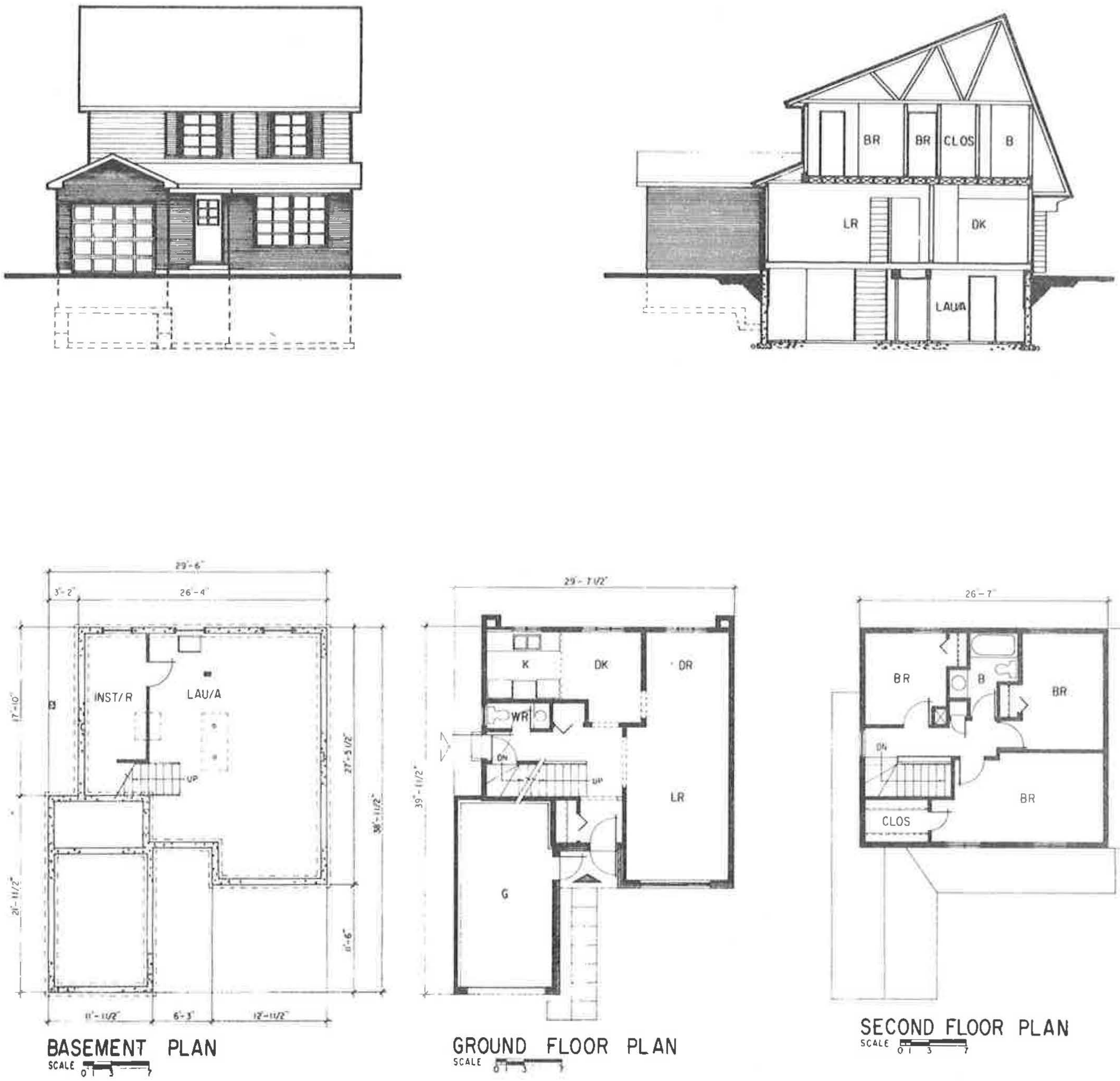


FIGURE 1

SITE PLAN - MARK XI PROJECT



BASEMENT PLAN

GROUND FLOOR PLAN

SECOND FLOOR PLAN

FIGURE 2

TYPICAL ARCHITECTURAL DESIGN OF ALL 4 HOUSES

Table 1

Thermal Properties of the Mark XI Houses*

	H1	H2, H3, H4
Ceiling	R = 3.5 (20)	R = 5.6 (32)
Walls	R = 2.1 (12)	R = 3.5 (20)
Basement walls	R = 1.2 (7) insulation to 0.9 m below grade on interior of wall	R = 1.3 (7.5) insulation to full height on exterior of wall
Windows	sealed, double-glazed, wood-frame, sliding and double-hung	sealed, triple-glazed, wood-frame, casement and awning
Exterior doors	insulated steel doors	insulated steel doors with storm doors
Air-vapour barrier	paper backing on glass-fibre batts	0.10 mm (4 mil) polyethylene sheet throughout

*R-values in this table and paper are given in SI units with Imperial units in brackets.

In addition, there are two nonstandard construction features in some of these houses; namely, continuous-span floor joists with glued subfloors and eight different panel materials used as roof sheathing.

The Eastern Forest Products Laboratory of Forintek Canada Corp. has been monitoring these features. One energy-related conclusion obtained from its floor study is that insulation should be on the outside of the floor joist headers to avoid condensation; further information on this aspect is given in Reference (3). Results of the first roof-sheathing inspection done in 1980 are reported in Reference (4).

All four houses have central forced-air electric furnaces. The furnace in H3 was the back-up heater for an air-heating solar system. The electric furnace in H4 was the back-up heater for an air-source heat pump.

The following seven studies were conducted and documented by the Division of Building Research. The references at the end of this Note contain additional information on these studies. Data from detailed monitoring are also available from the Division.

THERMAL PERFORMANCE OF STANDARD AND UPGRADED HOUSES

The measured energy losses and gains are given in Table 2 for the 1978-79 heating season (4754 degree-days).

Table 2

Energy Comparison of H1 and H2*
(1978-79)

	H1 MW•h	H2 MW•h
Total purchased heating energy	16.3	11.3
Gains from appliances, lights, sun and people	7.5	7.4
Total building energy loss	23.8	18.7

*Taken from Reference (2)

The results can be summarized as follows:

- the upgraded house H2 required 31% less purchased heating energy than the standard house H1;

- the occupancy and solar gain for each of the houses totalled 7.5 MW•h for the heating season; this is equivalent to 32% and 40% of the total heat requirement for H1 and H2, respectively;
- H2 had 21% less heat loss than H1.

Table 3 compares the calculated and experimental results for the design load and annual heat consumption for H1 and H2.

Table 3

Design Load and Annual Heat Consumption*

	H1 calcd.	H1 exptl.	H2 calcd.	H2 exptl.
Design heating load (kW)	13.7	7.1	8.5	5.3
Annual heat energy consumption (MW·h)	20.2	16.0	12.5	11.1

*The calculated values are ASHRAE modified degree-day (MDD) method results and are taken from Reference (1); the experimental values are derived from Reference (2).

The design heating load is used to size heating systems. Table 3 indicates that the usual MDD method of calculation gives results for H1 and H2 that exceed the experimental values by 93% and 60%. The values for the annual heat consumption using the MDD method are higher than the experimental values by 26% and 13%.

Table 4 shows the heat loss distribution for H1 and H2.

Table 4

Comparison of Heat Loss Distribution for H1 and H2*

	H1 calcd.	H1 exptl.	H2 calcd.	H2 exptl.
Above-grade envelope	58%	63%	62%	62%
Below-grade envelope	10%	23%	12%	26%
Air leakage	32%	14%	26%	12%

*The calculated values are taken from Reference (1) using the MDD method; the experimental values are derived from References (2) and (5).

It is interesting to note in Table 4 that although there is close agreement between the calculated and experimental above-grade envelope losses, there are large discrepancies for the below-grade envelope and air-leakage losses. This may explain the large disagreement in Table 3 between the experimental and MDD results, and suggests the need to improve or change some of the calculation methods used in this project.

THERMAL PERFORMANCE OF THE UPGRADED WALL SYSTEM

Houses H2, H3 and H4 have an upgraded wall system (illustrated in Figure 3). The thermal performance of the upgraded wall systems in H2 and H4 was monitored during the heating season of 1980-81 to:

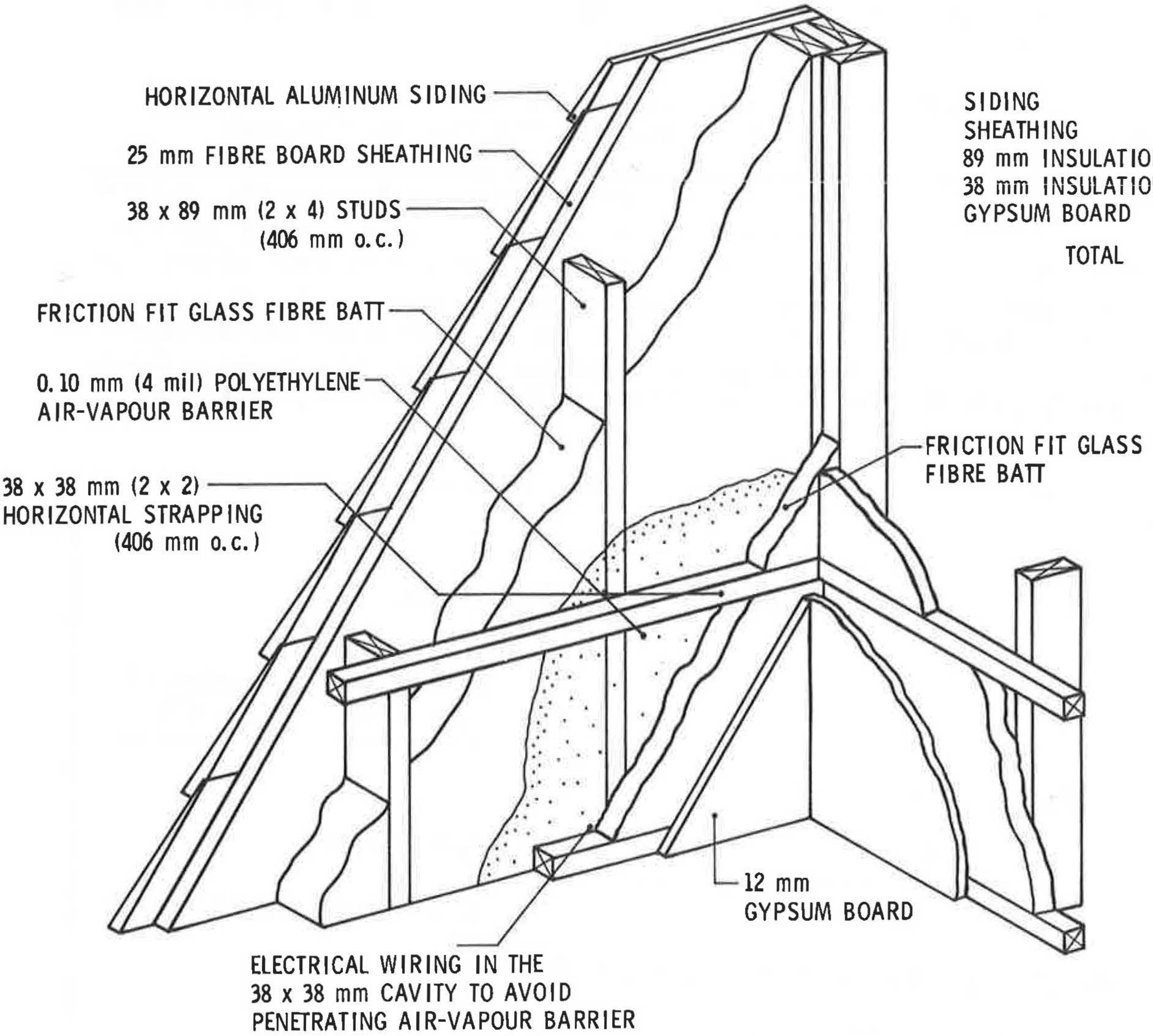
- compare measured R-values with calculated R-values;
- determine the effect of framing members on the R-value of the wall system.

Measurement and equipment details are given in Reference (6). Table 5 gives a summary of both measured R-values and R-values calculated using standard ASHRAE procedures. The mean temperature, T_M, is the average of the inside and outside surface temperatures. A T_M of 24°C is the reference temperature for laboratory measurements and for tables of R-values. A T_M of 9°C corresponds to the average winter air temperature of -2°C for Ottawa from October through April. The reference point of T_M = 9°C is given since it represents the average field performance, whereas T_M = 24°C is the laboratory reference point. Generally, the R-value of insulations increases as the T_M decreases.

Table 5

Upgraded Wall System R-values

	R-value at T_M = 24°C	R-value at T_M = 9°C
Insulation (through cavity)		
- calculated	3.78 (21.5)	---
- measured (average of north and south wall)	3.76 (21.3)	4.14 (23.5)
Wall System (through cavity and studs)		
- calculated (thermal bridging through framing members)	3.53 (20.0)	---
- measured (average of north and south wall)	2.93 (16.6)	3.23 (18.3)



	RSI
SIDING	0.18
SHEATHING	0.53
89 mm INSULATION	2.11
38 mm INSULATION	0.88
GYPSUM BOARD	0.08
TOTAL	3.78

FIGURE 3
UPGRADED WALL SYSTEM

The results shown in Table 5 indicate that:

- the R-values calculated and measured through the insulation for T_M = 24°C agree;
- the measured R-value of the insulation for the average winter temperature (T_M = 9°C) is 4.14 which is 10% more than the standard calculation (T_M = 24°C);
- the measured R-value through the wall system for T_M = 24°C is 17% less than the calculated R-value; this difference is probably due to the nails in the wall/siding and to nonparallel heat flows in the wall;
- the measured R-value of the wall system for the average winter temperature (T_M = 9°C) is 3.23; hence, the thermal performance of the wall in winter is 8% less than that predicted by the standard calculation.

BASEMENT STUDIES

The thermal performance of the basement walls and floors of H1 and H4 were monitored from January to April 1979. The results can be summarized as follows:

- the heat loss rates of the below-grade walls and floors appear to be independent of the outdoor temperature;
- the total below-grade heat loss rate for the 1978-79 heating season was estimated to be 1.02 kW for H1 and 0.94 kW for H4 (8% less);
- the full-height insulation in H4 reduced the heat loss of the basement walls by 11% compared to H1;
- the west wall in the H4 basement, which is adjacent to another heated basement, had a heat loss 30% lower than that of the north wall facing the street.

More information is given in Reference (2).

In the summer of 1980 several sections of the basement wall of H1 were reinsulated full height on the interior to R 3.5 (20) by using a variety of insulation materials and techniques. Thermal and moisture measurements are being carried out to evaluate the performance of the wall.

Two cracks in one basement wall of H2 are being monitored for variation in width. The pattern of the cracks suggests that the wall may have been bumped during backfilling.

The water flow in the drainage tile around H4 was occasionally monitored since water flow around the basement can affect basement heat loss.

AIR-LEAKAGE STUDIES

The standard house (H1) was built using paper-backed glass-fibre batts. The upgraded houses (H2, H3, H4) contained additional insulation and a specially applied 0.10 mm (4 mil) polyethylene air barrier to improve air-tightness of the house envelope. A comparison of the air leakage rates of the two air-barrier systems shows their relative effectiveness. During the 1978-79 studies, all four houses were heated by electric furnaces. H3 had, in addition, an air-based solar heating system and H4, a heat pump system. None of the houses, therefore, had a chimney.

Air-Tightness

Air-tightness is represented by the air leakage into a house resulting from a pressure difference across the building envelope induced by mechanical means. In 1978 and 1979, air-tightness tests were performed on all four Mark XI houses (H1, H2, H3, H4) using the fan pressurization method. (Full results are given in Reference (5).) The air-leakage rate was measured over a range of induced pressure differences from 8 to 80 Pascals (Pa).

Table 6 shows some of the results from tests conducted in March 1979.

Table 6

Air-Tightness Results
(March 1979)

	Air-leakage rate (L/s) for:		Improvement in air-tightness	ELA*
	ΔP = 50 Pa	ΔP = 10 Pa	compared to H1	m^2
H1, (standard)	403	128	0%	0.053
H2, (upgraded)	249	79	38%	0.033
H3, (upgraded + solar)	373	119	7%	0.049
H4, (upgraded + heat pump)	275	87	32%	0.036

*ELA is the equivalent leakage area calculated according to the Draft Standard CGSB 149-GP-10 (ΔP = 10 Pa).

The results show that the upgraded houses H2 and H4 are significantly tighter than H1, whereas the solar house H3 is only slightly tighter than H1.

The air-leakage rates were, on average, 10% higher than the values obtained a year earlier. This increase is attributed to the increase in leakage openings caused by the drying and shrinkage of building materials.

On comparing the air-tightness measurements carried out in 1978 on 63 houses built in Ottawa (Reference (7)), with those on the four Mark XI houses for 1978-1979, it can be seen that both H1 and H3 exceed the lower limit of these 63 houses, while H2 and H4 fall below it. The average air-leakage rate for H2 and H4 is 47% of the average for the 63 houses.

Air Infiltration

Air infiltration is the uncontrolled leakage of air into a house resulting from pressure differences across its envelope induced by wind and inside-to-outside temperature differences. Air infiltration rates (natural air change rates) were measured simultaneously in both H1 and H4 between January and April 1979 using the tracer-gas decay method with carbon dioxide (CO_2) as the tracer gas. (Reference (5) gives complete information on these tests.) The average results for winter weather conditions ($\Delta t > 20°C$ and wind velocity > 3.5 m/s) were 0.3 and 0.2 air changes per hour (AC/h) for H1 and H4, respectively.

The Mark XI houses provided a unique opportunity to investigate the correlation between air infiltration and air-tightness for chimneyless houses with identical location and surroundings. Reference (8) shows a direct correlation, thus showing that the air change rates for the Mark XI houses can be derived from their air-tightness measurements. This knowledge is valuable since it means that fan pressurization measurements, which are easier, quicker and cheaper to carry out than those using tracer-gas methods, can replace the latter.

During the 1980-81 heating season a study was carried out on H3 to determine the effect of a gas furnace and chimney on the house air leakage (Reference 9).

Some of the results for H3 are as follows:

- the air-tightness value with the chimney uncapped was about 9% greater than with the chimney capped;
- switching from electric furnace to gas furnace operation resulted in a 50% increase in the air infiltration rate (wind speeds <3.5 m/s);
- about 60% of the inside air exhausted to the outside through the chimney, and the remaining 40% exfiltrated through the upper portion of the house envelope.

The interaction between mechanical ventilation systems and air leakage is still being studied.

AIR-SOURCE HEAT PUMP SYSTEMS

One of the upgraded houses, H4, was used from 1978 to 1981 to study the thermal performance of air-source heat pump systems as heating systems. It was heated during the first two heating seasons by a heat pump of nominal 2½-ton (9 kW) capacity with three 4.6 kW stages of electric resistance heaters and demand defrost. During the third heating season, a heat pump of nominal 1½-ton (5.4 kW) capacity with two 4.6 kW stages of electric resistance heaters and demand defrost was used. The latter heat pump size was the closest match to the house load according to conventional sizing practice.

The seasonal performance factor (SPF) for the heat pump and electric heaters equals the total heat they supply divided by the total energy they use. The SPF is calculated for the heating season and is always greater than 1.0 since the heat pump supplies more energy than it uses while extracting heat from the outside air.

Table 7 compares the heat pump performance for the three heating seasons. Reference (10) gives further information.

Table 7

Heat Pump Results

	2½-ton		1½-ton
	1978-79 (Dec.-May)	1979-80 (Sept.-May)	1980-81 (Sept.-May)
Degree-days (% of average for period)	99%	96%	102%
Seasonal performance factor (SPF)	1.5	1.7	1.6
Energy supplied by heat pump	81%	88%	76%
Energy supplied by resistance heaters	19%	12%	24%
Energy savings due to heat pump	32%	41%	39%

These energy savings, which average about 40% for 1979-81, are indicative of the performance of any air-source heat pump in the Ottawa region. The savings should be higher in warmer regions and lower in colder regions. Since the 1½-ton heat pump showed energy savings as high as or higher than the 2½-ton heat pump (for equivalent degree-days), the cost of the larger size may not be justified for this particular house.

Some other aspects being studied include:

- variations of the SPF with different sizes of heat pumps used with the same house heating load;

- the development of a method to calculate the SPF so that energy savings can be predicted;

- a comparison of demand defrost with timed defrost.

In 1981-82 a new 2½-ton heat pump with two parallel-running compressors will be used as the heating system. Other features include two 5 kW stages of electric resistance heaters and timed defrost. With the original 2½-ton heat pump, assistance was required from the electric heaters below -15°C; in this two-compressor model the second compressor comes on at -15°C to assist the first compressor. This means that the electric heaters will not be needed until a much lower temperature.

SOLAR HEATING SYSTEM

The solar heating system installation in H3 was completed in December 1977. Some of the characteristics of the system are as follows (see Reference (11) for full details):

- a pre-engineered system made available in 1976;

- an active system which runs in series with a 10 kW electric furnace;

- 35 m^2 air-heating flat-plate collectors;

- 5 m^3 pebble-bed heat storage;

- an air-to-water heat exchanger for preheating hot water.

During the 1978-79 heating season the system performed poorly. An examination of the system in the spring of 1979 showed two serious faults: a malfunctioning damper and substantial air leaks throughout the system. Most problems were corrected where feasible.

During the 1979-80 heating season, several problems persisted:

- there was significant overheating of the indoor space on sunny spring, summer and fall days;

- there was condensation on the inner glazing of all collector panels;

- air leakage problems continued.

The solar system was disconnected in the fall of 1980 so that H3 could be used for other experiments.

Table 8 shows the results of air infiltration measurements performed on H3 in March 1980. The average air change rate for the heating season was estimated from these data to be 0.26 AC/h.

Table 8

Air Change Rates for H3
(March 1980)

Air change rate AC/h	Time spent in mode	Operating mode
0.23	88%	solar collection fan "off"
0.49	10%	solar collection fan "on" in storing-heat mode
0.66	2%	solar collection fan "on" in heating-from-collector mode

The average solar collection efficiency was 32% for the 1979-80 heating season; 61% of the energy put into storage was later recovered as usable heat. The over-all energy results are given in Table 9.

Table 9

Energy Supplied to H3 During 1979-80 Heating Season

	Space-heating energy MW•h	Hot-water energy MW•h	Total energy MW•h
Electric	7.9 (54%)	2.8 (57%)	10.7 (55%)
Solar	6.7 (46%)	2.1 (43%)	8.8 (45%)

From Table 9 we see that the solar heating system supplied 45% of the space-heating and hot-water energy demand for H3.

Even though a comparable installed solar heating system today would cost about 1/3 of the 1977 price, conventional energy conserving options would be more attractive as energy-saving investments.

FIELD PERFORMANCE OF A NATURAL GAS FURNACE

The solar heating system of H3 was disconnected in the fall of 1980 and a gas furnace and gas vent (chimney) were installed. The objective was to study the field performance of a gas furnace in an unoccupied house during the winter of 1980-81.

The furnace and system characteristics were as follows:

- nominal 40,000 Btu/h input and 32,000 Btu/h output;
- a standing pilot light;

- no special energy-conserving features;
- combustion air drawn from the basement;
- a chimney consisting of a class B vent 12.7 cm (5 in.) in diameter which extended through the roof.

The gas furnace was connected in parallel with a 10 kW forced-air electric furnace; each furnace was used alternately for two-week periods. The gas vent was capped when the electric furnace was in operation. (Further information is given in Reference (12).)

The steady-state efficiency in percentage is the useful heat supplied by the furnace divided by the heat content of the natural gas input to the furnace (multiplied by 100). This is measured with the burner running continuously at optimum operating conditions. For H3 the steady-state efficiency at the start of the heating season was 74% as measured by the Canadian Combustion Research Laboratory of Energy, Mines and Resources Canada. At the end of the heating season, it was discovered that the furnace was underfiring; hence, all the percentage results reported for this period would have been slightly higher for the properly adjusted furnace.

The gas-furnace-system efficiency at a given indoor-outdoor temperature difference (given as a percentage) is the ratio of the house-heating load to the energy content of the gas input multiplied by 100. It should be noted that the increase in heat loss due to the air flow through the gas vent is not considered as part of the house-heating load. The system efficiency was 50% for a 10°C temperature difference (low-load situation) and rose to 65% for a 50°C temperature difference (high-load situation). The furnace was slightly oversized for the house-heating load for H3 since it ran 84% of the time (instead of 100%) at the Ottawa design temperature difference of 47°C.

The seasonal efficiency as a percentage is the heat energy required to maintain the house at the thermostat set point divided by the energy content of the gas input for the heating season multiplied by 100. The seasonal efficiency for the gas furnace was calculated to be 60%.

A steady-state efficiency result of 74% is the highest possible percentage since the only heat energy lost by the furnace is the sensible and latent heat in the flue gases going up the chimney. A maximum (high-load) system efficiency of 65% is a lower percentage since the house has lost additional heat due to extra air leakage caused by the operation of the furnace and the chimney. A seasonal efficiency of 60% is lower still since it is the average of the system efficiencies during the heating season.

Similar studies will be carried out during the 1981-82 heating season on two gas furnaces with higher efficiency; that is, an induced-draft spark-ignition gas furnace and a condensing gas furnace.

MECHANICAL VENTILATION WITH HEAT RECOVERY

Ontario Hydro installed and operated a mechanical ventilation system with a rotary heat exchanger in H2 from December 1978 to April 1979, which was used with a forced-air electric heating system with no chimney. (See Reference (13) for full details.) During most of this period the house was occupied by two adults and two children. The objectives of this experiment were to assess the economic viability of heat recovery and to assess the capability of mechanical ventilation in controlling indoor humidity.

Savings of 5020 kWh per heating season were projected for the 85% efficient heat exchanger. The occupants produced an average of 11.8 kg/day of moisture. Table 10 shows the effects of ventilation rates on air change rate and indoor relative humidity.

Table 10

Ventilation Rates and Indoor Humidity

Mechanical ventilation rate (m^3/min)	Air change rate (AC/h)	Maximum relative humidity reached
0	0.15	55%
1.7	0.40	39%
2.3	0.49	37%

Both of the non-zero mechanical ventilation rates in Table 10 produced air change rates high enough to control indoor air contaminants and keep the indoor relative humidity below 40%.

The following pages describe some Mark XI studies for which no project reports have yet been issued.

HUMIDITY AND AIR CHANGE

An experiment was conducted to investigate indoor moisture loss as an indicator of air leakage. The amount of water used by a humidifier to maintain a relative humidity of 40% was measured for several months. All four houses were tested while unoccupied from March to May 1978; only H3 and H4 underwent additional tests from January to April 1979. The results are being analyzed.

MOISTURE STUDIES

Moisture pins to monitor moisture levels were installed during construction in 1977 on the warm side of the polyethylene air-vapour barrier throughout the building envelope of all four houses. There are no condensation problems for the areas of the building assemblies containing at least two thirds of their R-value on the outside (cold side) of the air-vapour barrier. This concurs with the dew point predictions. However, in the first- and second-floor joist headers of H2, H3, and H4, all the insulation is located on the inside of the air-vapour barrier; as a result, the moisture pins have shown high moisture levels in winter which return to normal by summer. The first-floor joist headers, which are accessible from the basement, were retrofitted with paper-backed glass-fibre batts which lowered the moisture content to acceptable levels. Unfortunately, the second-floor joist headers could not be modified since the construction detail used for these headers made them inaccessible. To avoid similar situations in the future, a different construction detail should be used.

The standard house, H1, has been occupied since April 1979 by a family of two adults, two children, and two pets. It has experienced interior condensation problems as evidenced by water streaming down windows and staining walls. This house has an electric furnace forced-air heating system and no chimney. The 24-hour average indoor relative humidity during cold weather (e.g. -14°C) was 35%. One or more forced ventilation systems will be used during the 1981-82 heating season to alleviate the problem of condensation. H1 is the only house presently occupied and the only one to have been occupied for more than a few months.

WIND AND PRESSURE EFFECTS

H3 has been instrumented since the fall of 1980 to measure the effects of wind on pressure differences throughout the building assemblies. This continuing project will help researchers to advise designers and builders by providing information on:

(1) what kind of pressure differences develop across walls, windows and ceilings in small buildings;

(2) which building components are providing air resistance in walls and ceilings;

(3) how the pressure load is transferred through the building assemblies.

PROJECT PARTICIPANTS

Division of Building Research (NRC)
HUDAC Task Force on Mark XI
Ontario Hydro
Consumers Gas
Forintek Canada Corp.
Canadian Combustion Research Laboratory (EMR)
Talback Construction

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