THE PERFORMANCE OF ENERGY-EFFICIENT RESIDENTIAL BUILDING ENVELOPE SYSTEMS

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ABSTRACT

A three-year field study was carried out to evaluate the performance of the building envelope systems used in 24 new, energy-efficient, and conventional houses. Ten of the houses were constructed with polyethylene air barriers, while 14 used the airtight drywall approach (ADA). Assessments of envelope performance were made using wood moisture content (WMC) measurements, thermographic inspections, and airtightness tests. The study concluded that the energy-efficient building envelope systems performed better than the conventional envelope systems, although both types provided satisfactory performance. Wall and attic WMC levels were lower in the energy-efficient houses and fewer WMC excursions (to potentially serious levels) were recorded. The energy-efficient houses also displayed fewer thermographic anomalies, particularly those of a severe nature. No evidence of interstitial condensation was found in either type of construction. These results demonstrated that energy-efficient construction techniques, if properly applied, can improve building envelope performance relative to conventional construction practices. The study also concluded that the polyethylene air barrier systems performed slightly better than those that used the ADA system, although both provided satisfactory performance. WMC levels were lower in the polyethylene houses and there were fewer thermographic anomalies.

INTRODUCTION

Background

The purpose of the building envelope is to provide protection from cold, heat, moisture, wind, and noise. Because it is exposed to a continuing array of thermal, structural, and moisture stresses, the envelope's performance can degrade over time. This may result in localized or general failure of the structure and can necessitate extensive repairs. During the last decade, concerns have been expressed about the adequacy and durability of residential building envelope systems constructed with high levels of thermal insulation and well-sealed air/vapor barriers. These concerns have increased with the development of new methods of providing air and vapor barrier protection, such as the airtight drywall approach (ADA), for which there is comparatively limited experience.

Study Objectives

The purpose of this study was to evaluate and document the performance of various types of building envelope systems under actual field conditions. The specific objectives were to

1. monitor and compare the performance of energy-efficient building envelope systems relative to those constructed using conventional methods,
2. search for evidence of envelope degradation that might occur during the first few years of occupancy,
3. investigate whether unacceptably high moisture levels are encountered in the building envelopes of energy-efficient houses, and
4. compare the performance of envelope systems constructed with polyethylene air barriers to those employing the ADA system.

DESCRIPTION OF THE MONITORING PROGRAM

Overview

The monitoring program consisted of a three-year field study of 20 energy-efficient and four conventional houses built between 1985 and 1989. All were detached bungalows with full basements, constructed by a single tract builder. Brief summaries, complete with descriptions of the air and vapor barriers, are provided in Tables 1 and 2. The houses were built in Winnipeg, Canada—a city with a cold, dry climate and relatively severe winters. It experiences 10,679 heating degree-days (5,889°C) and has a 97.5% winter design temperature of −27°F (−33°C). Precipitation averages 21 in. (52.6 cm) per year and summer daytime relative humidity levels are typically in the range of 30% to 60%. The summer dry-bulb design temperature is 86°F (30°C).

Each of the 24 project houses was classified as either energy-efficient or conventional based on the design of its air barrier. Insulation levels were not used to categorize them because all were relatively well insulated.

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TABLE 1 **Description of Project Houses**

	Building Envelope					Mechanical Systems			
House	Wall Construction	Exterior Wall Finish	Basement Construction	Ceiling/Attic Construction	Windows	Space-Heating System	Ventilation System	Year Completed	Energy Standard
1-6	2x6 (38x140), Rigid Glass Fiber Insulated Sheathing (Reversed) c/w SBPO Air Retarder	Stucco with Wood or Brick Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed, Awning and Casement	Electric Forced Air Furnace	Heat Recovery Ventilator	1985	R-2000
7,8	2x6 (38x140)	Stucco with Wood Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed, Awning and Casement	Electric Forced Air Furnace	Central Exhaust with Make-Up Air Duct	1985	Conventional
9,10	2x6 (38x140)	Stucco with Stone and Wood Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed, Awning and Casement	Gas Forced Air Furnace	Bathroom Exhaust Fan	1985	Conventional
11-14	2x6 (38x140), Rigid Glass Fiber Insulated Sheathing c/w SBPO Air Retarder	Stucco with Wood, Brick or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning and Casement	Electric Baseboards or Forced Air Furnace	Exhaust-only Heat Pump or Heat Recovery Ventilator	1986	R-2000
15,16	Double Wall	Stucco with Wood Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning and Casement	Air-to-Air Heat Pump	Integrated with Space Heating System	1986	R-2000
17,18	Double Wall	Stucco with Brick, Wood or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning and Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
19,20	2x4 (38x89), Rigid Extruded Polystyrene Sheathing	Stucco with Wood and Brick Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning and Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
21	Predominantly 2x6 (38x140) with Interior Strapping	Vinyl and Wood Siding	Cast Concrete	Cathedral and Truss Ceilings	Several Types	Several Types	Several Types	1989	R-2000
22	2x6 (38x140)	Stucco with Wood and Brick Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed and Awning	Electric Forced Air Furnace	Central Exhaust	1988	Energy Efficient
23	2x6 (38x140) with Interior Strapping	Stucco with Wood Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed and Awning	Electric Forced Air Furnace	Heat Recovery Ventilator	1988	R-2000
24	2x6 (38x140) with Extruded Polystyrene Sheathing	Stucco with Wood and Brick Siding	Cast Concrete	Cathedral and Truss Ceilings	Triple-Glazed; Fixed, Awning and Casement	Electric Baseboards and Radiant Panels	Heat Recovery Ventilator	1988	R-2000

Evaluation Methods

To assess building envelope performance, three complementary evaluation techniques were used:

- wood moisture content (WMC) measurements of framing members,
- thermographic examinations, and
- airtightness tests.

Wood Moisture Content

The wood moisture content is defined as the weight of water contained in a wood sample, expressed as a percentage of the oven-dry weight of the sample. Lumber used for residential construction in Canada is required by the National Building Code to have a moisture content not exceeding 19%. Wood is a hygroscopic material, i.e., it absorbs and releases moisture in response to changes in the relative humidity of the surrounding air. Because it is an organic material, wood is susceptible to fungal decay. For this to occur, five conditions must be satisfied: oxygen must be present, the temperature must be between about 40°F and 105°F (4°C and 41°C), a food source must be present (the wood), a source of infection must exist (typ-

TABLE 2 Air and Vapor Barrier Details

House	Air Barrier: Type	Sealing Method: Headers	Sealing Method: Cantilevers	Sealing Method: Partition Walls at Ceiling	Sealing Method: Window and Door Rough Openings	Sealing Method: Electrical Outlets	Crew	Vapor Barrier: Walls	Vapor Barrier: Ceiling	Vapor Barrier: Basement
1-6	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes and Gaskets	A	Paint	Paint	Paint
7,8	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes and Gaskets	A	Paint	Paint	Paint
9,10	4 mil Polyethylene	None	None	Unsealed Polyethylene	Unsealed Polyethylene	Unsealed Polyethylene	A	Polyeth ylene	Polyeth ylene	Polyeth ylene
11-14	Simplified ADA	None	None	None	Ethafoam Rod Gaskets	Poly-Pan Boxes and Gaskets	B	Paint	Paint	Paint
15,16	6 mil Polyethylene	Caulking	Caulking	Sealed Poly-ethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyeth ylene	Polyeth ylene	Polyeth ylene
17,18	6 mil Polyethylene	Caulking	Caulking	Sealed Poly-ethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyeth ylene	Polyeth ylene	Polyeth ylene
19,20	ADA	Closed Cell Polyethylene and Neoprene Gaskets	Closed Cell Polyethylene and Neoprene Gaskets	Neoprene Gaskets	Ethafoam Rod Gaskets	Poly-Pan Boxes and Gaskets	B	Paint	Paint	Paint
21	Primarily 6 mil Polyethylene	Sealed Polyethylene	Sealed Polyeth-ylene and SBPO Air Retarder	Sealed Poly-ethylene	Various	Sealed Polyethylene	C	Polyeth ylene	Polyeth ylene	Polyeth ylene
22	Primarily 6 mil Polyethylene	Sealed Polyethylene and SBPO Air Retarder	Sealed Polyeth-ylene and SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyeth ylene	Polyeth ylene	Polyeth ylene
23	6 mil Polyethylene	Sealed Polyethylene and SBPO Air Retarder	Sealed Polyeth-ylene and SBPO Air Retarder	Sealed Poly-ethylene	Various	Sealed Polyethylene	D	Polyeth ylene	Polyeth ylene	Polyeth ylene
24	6 mil Polyethylene	Sealed Polyethylene and SBPO Air Retarder	Sealed Polyeth-ylene and SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyeth ylene	Polyeth ylene	Polyeth ylene

ically from airborne spores), and finally, moisture must be present. The optimum moisture content for fungal growth is about 30%, whereas wood with a moisture content of 19% or less generally is considered safe from most types of fungal attacks.

The wood moisture content of framing members was monitored in 18 of the 24 houses using permanently installed moisture pins embedded at various locations in the walls and roof trusses. A total of 516 sets of pins was installed at the time of construction, and the moisture content was measured roughly once per month. More than 13,000 WMC measurements were made during the three-year monitoring period. Instrumented wall cavities typically were outfitted with four monitoring "stations," with each station consisting of two sets of moisture pins and a thermocouple. The first set of pins measured the shell WMC ¼ in. (6 mm) below the wood surface, while the second measured the mid-depth (core) moisture content. The thermocouple was located between the two sets of pins along an isotherm to permit temperature corrections of the meter readings. All moisture pins were installed parallel to the wood grain. Instrumented cavities typically were equipped with four stations, two on the stud and one on each of the top and bottom plates. The stud stations were located 1 in. (25 mm) from the warm and cold faces, respectively, while the plate stations were both located 1 in. (25 mm) from the cold faces. Station positions were selected to avoid knotholes, nails, and other anomalies.

Some additional monitoring stations were installed in several wall cavities containing construction anomalies, such as windows, electrical outlets, and corner framing. Wood moisture monitoring stations were installed on the top and bottom chords of the roof trusses in several houses.

The monthly WMC data were recorded in a data base in which the raw meter readings were edited and corrected for temperature and wood species. Garrahan et al. (1991) recommend the following relationship:

$$M_c = \{ [(M + 0.567 - 0.0260T + 0.000051T^2) / (0.881)\ (1.0056)^T] - b \} / a \quad (1)$$

where

M_c = corrected moisture content (%),
M = uncorrected meter reading (%),
T = wood temperature (°C), and
a, b = species correction coefficients.

Based on personal communication with the authors, the following approximation to this complex equation was used for interpreting the field measurements:

$$M_c = (S - 0.0081T)\, M + (0.57 - 0.043T) \quad (2)$$

where S = species correction constant (1.45, used for spruce-pine-fir).

The WMC data were analyzed by defining and evaluating three parameters for each of the 516 monitoring locations:

- Mean WMC: The mean WMC recorded during the monitoring period; this described the long-term moisture content of the wood.
- Measurements Exceeding 19%: The number and percentage of WMC measurements that exceeded 19% at each location were calculated to identify the number of occurrences at which the wood was theoretically vulnerable to decay. Data collected during the initial (one- to two-month) dry-out period were excluded.
- Stability Below 19%: Because individual excursions above 19% do not necessarily represent a hazard, provided the wood returns to a dry condition before significant decay has taken place, each monitoring location was categorized as either "stable" or "not stable" below 19%. A location was judged as not stable if (a) two consecutive monthly measurements were recorded above 19% or (b) three measurements above 19% were recorded during the entire monitoring period. Data collected during the initial (one- to two-month) dry-out period were excluded.

TABLE 3 **WMC Summary—Conventional Houses**

	Mean WMC (%)		Measurements Exceeding 19%				Locations Not Stable Below 19%			
			Walls		Attics		Walls		Attics	
House	Walls	Attics	No.	%	No.	%	No.	%	No.	%
Polyethylene										
9	10.3	9.9	2	0.4	2	3.3	0	0.0	0	0.0
10	11.3	9.0	0	0.0	0	0.0	0	0.0	0	0.0
ADA										
7	12.8	8.3	36	7.5	0	0.0	2	13.0	0	0.0
8	12.0	9.1	27	5.9	0	0.0	4	25.0	0	0.0
Means:										
Poly	10.8	9.5	2	0.2	2	1.6	0	0.0	0	0.0
ADA	12.4	8.7	63	6.7	0	0.0	6	18.8	0	0.0
All	11.6	9.1	65	3.4	2	0.8	6	9.4	0	0.0

TABLE 4 **WMC Summary—Energy-Efficient Houses**

	Mean WMC (%)		Measurements Exceeding 19%				Locations Not Stable Below 19%			
			Walls		Attics		Walls		Attics	
House	Walls	Attics	No.	%	No.	%	No.	%	No.	%
Polyethylene										
15	9.0	8.2	0	0.0	0	0.0	0	0.0	0	0.0
16	9.3	8.2	0	0.0	0	0.0	0	0.0	0	0.0
23	10.4		3	0.9			1	3.0		
ADA										
1	10.4	7.9	0	0.0	0	0.0	0	0.0	0	0.0
2	11.2	8.7	0	0.0	0	0.0	0	0.0	0	0.0
3	10.9	8.7	0	0.0	0	0.0	0	0.0	0	0.0
4	11.2	9.1	6	1.3	0	0.0	0	0.0	0	0.0
5	10.5	8.3	10	1.7	0	0.0	1	5.0	0	0.0
6	11.5	9.1	4	0.8	0	0.0	1	6.0	0	0.0
11	10.2	8.9	0	0.0	0	0.0	0	0.0	0	0.0
12	9.4	8.9	1	0.1	0	0.0	0	0.0	0	0.0
19	10.1	9.1	0	0.0	0	0.0	0	0.0	0	0.0
20	9.7	8.8	0	0.0	0	0.0	0	0.0	0	0.0
Means:										
Poly	9.6	8.2	3	0.2	0	0.0	1	1.1	0	0.0
ADA	10.5	8.8	21	0.3	0	0.0	2	0.8	0	0.0
ALL	10.3	8.7	24	0.3	0	0.0	3	0.9	0	0.0

Tables 3 and 4 summarize the mean wall and attic WMC values, the number and percentage of readings above 19%, and the number and percentage of locations that were judged as not stable below 19%.

Thermographic Examinations

Thermographic examinations were conducted in accordance with CGSB Standard 149-GP-2MP (CGSB 1986b) using an infrared thermovision scanning imager, with an SW, f1.8, 20° lens, and with the display equipped with dual isotherm indicators. Thermographic scans were made of the building interiors with the houses depressurized at 35 to 45 pascals (Pa) below ambient and with an indoor-to-outdoor temperature differential of at least 27°F (15°C). AFter thermal equilibrium had been established, the houses were systematically examined from a series of similar inspection stations. Scans in subsequent years were conducted from these same locations to provide a consistent vantage point. The entire visible main floor envelope area was scanned during each visit and if a thermal anomaly was identified, digital and analog records were made for later reference and analysis. A total of 1,013 thermographic images were recorded. Each anomaly was analyzed and its type and strength assessed. Anomalies were categorized as air infiltration/exfiltration, interstitial air movement, condensation, insulation anomaly, or thermal bridging. In many instances, faults were categorized as a combination of two or more of the types. Anomaly strength was classified using a three-tiered rating system in which each anomaly was assessed a numerical value determined by comparing all thermograms of a similar or related location or feature:

- Numerical value 1: Minor anomalies evident with a generally uniform interior surface temperature.
- Numerical value 2: An anomaly or anomalies evident with a moderate change in the gray scale (of the thermogram) over a relatively moderate surface area.
- Numerical value 3: A significant anomaly or anomalies evident with an intense transition in the gray scale (i.e., indicating an abrupt decrease in local surface temperature) over a relatively large surface area.

To quantify the extent of the anomalies in each house, the concept of the "fault count" was created:

$$\text{Fault count} = (\text{No. of anomalies}) \times (\text{Average severity}). \tag{3}$$

One problem that was encountered during the thermographic examinations was restricted accessibility to some parts of the envelopes due to furniture, etc. This problem was mitigated by performing a subanalysis of the data for only those stations that were visible during all three examinations. These stations were termed *continuously visible.*

The thermographic data are summarized in Tables 5 through 8, which show the mean fault count data and severe fault data based on house type and air barrier system. Figures 1 through 4 show the mean fault count data and severe fault data for the continuously visible stations.

Airtightness

A total of 167 airtightness tests were conducted on a regular basis during the monitoring program in accordance with CAN/CGSB 149.10-M86 (CGSB 1986a). To evaluate changes in airtightness, specifically degradation caused by air barrier deterioration, three methods of comparison were used:

- Variation between the first and last airtightness tests—The absolute and percentage changes in airtightness were compared using the results of the first and last tests. Both the air change rate, at 50 Pa

TABLE 5 Mean Fault Count Summary

All Visible Stations

	Mean Fault Count					
	Conventional			Energy Efficient		
Year	ADA	Poly	All	ADA	Poly	All
1986	32.5	41.5	37.0	40.7	18.0	35.0
1987	32.0	43.5	37.8	32.4	14.5	27.9
1989	34.5	37.0	35.8	29.3	15.3	25.8

Fault Count = (No. of Occurrences) x (Average Severity)

Continuously Visible Stations

	Mean Fault Count					
	Conventional			Energy Efficient		
Year	ADA	Poly	All	ADA	Poly	All
1986	26.0	35.0	30.5	28.5	12.3	24.4
1987	30.5	41.0	35.8	30.8	13.8	26.6
1989	31.0	37.0	34.0	28.3	14.0	24.8

Fault Count = (No. of Occurrences) x (Average Severity)

TABLE 6 Severe Fault Summary

All Visible Stations

	Percentage of Stations with Severe Faults					
	Conventional			Energy Efficient		
Year	ADA	Poly	All	ADA	Poly	All
1986	11.0	5.5	8.0	6.8	1.5	5.4
1987	12.0	7.5	9.7	7.1	0.0	5.3
1989	14.0	5.5	9.5	5.2	0.0	3.8

Continuously Visible Stations

	Percentage of Stations with Severe Faults					
	Conventional			Energy Efficient		
Year	ADA	Poly	All	ADA	Poly	All
1986	10.0	5.5	7.6	5.4	0.0	4.1
1987	12.0	7.5	9.7	6.9	0.0	5.2
1989	13.0	5.5	9.0	5.2	0.0	3.8

TABLE 7 Mean Fault Count Summary

All Visible Stations						
	Mean Fault Count					
	Polyethylene			ADA		
Year	Conv.	Energy Effi.	All	Conv.	Energy Effi.	All
1986	41.5	18.0	25.8	32.5	40.7	39.5
1987	43.5	14.5	24.2	32.0	32.4	32.4
1989	37.0	15.3	22.5	34.5	29.3	30.0

Fault Count = (No. of Occurrences) x (Average Severity)

Continuously Visible Stations						
	Mean Fault Count					
	Polyethylene			ADA		
Year	Conv.	Energy Effi.	All	Conv.	Energy Effi.	All
1986	35.0	12.3	19.8	26.0	28.5	28.1
1987	41.0	13.8	22.8	30.5	30.8	30.8
1989	37.0	14.0	21.7	31.0	28.3	28.7

Fault Count = (No. of Occurrences) x (Average Severity)

TABLE 8 Severe Fault Summary

All Visible Stations						
	Percentage of Stations with Severe Faults					
	Polyethylene			ADA		
Year	Conv.	Energy Effi.	All	Conv.	Energy Effi.	All
1986	5.5	1.5	2.8	11.0	6.8	7.4
1987	7.5	0.0	2.5	12.0	7.1	7.8
1989	5.5	0.0	1.8	14.0	5.2	6.4

Continuously Visible Stations						
	Percentage of Stations with Severe Faults					
	Polyethylene			ADA		
Year	Conv.	Energy Effi.	All	Conv.	Energy Effi.	All
1986	5.5	0.0	1.8	10.0	5.4	6.1
1987	7.5	0.0	2.5	12.0	6.9	7.6
1989	5.5	0.0	1.8	13.0	5.2	6.3

(ac/h_{50}), and the normalized leakage area, at 10 Pa (NLA_{10}), were used. Since this method relies on only two measurements, it is susceptible to seasonally induced variations in airtightness if testing was performed during different seasons.

- Variation between the first and last seasonally coincident airtightness tests—Similar to method 2, except the seasonal impact is eliminated.
- Statistical tests—Degradation of airtightness was assessed by determining whether a relationship existed between the airtightness and time variables for each house. This can be expressed mathematically (using data of air change rate at 50 Pa as an example) with a regression equation of the form:

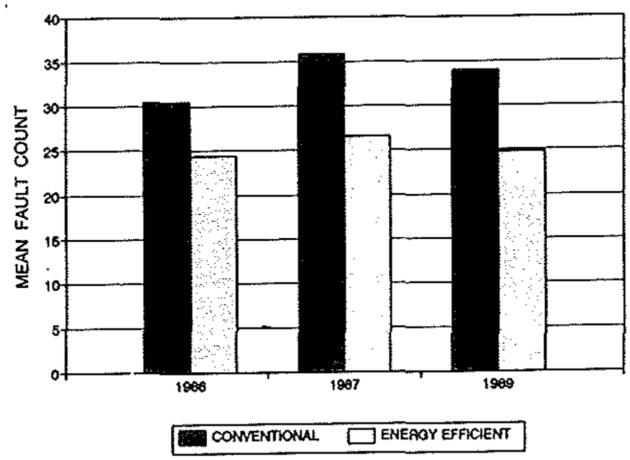

Figure 1 Continuously visible stations.

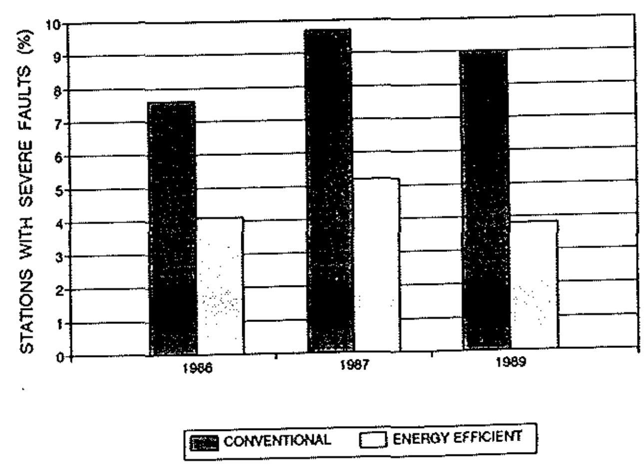

Figure 2 Continuously visible stations.

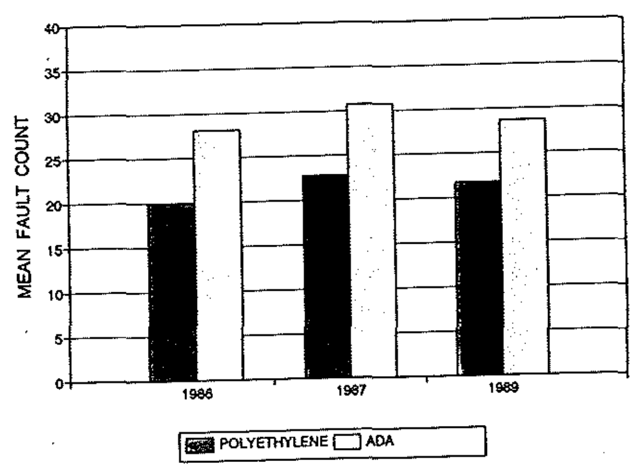

Figure 3 Continuously visible stations.

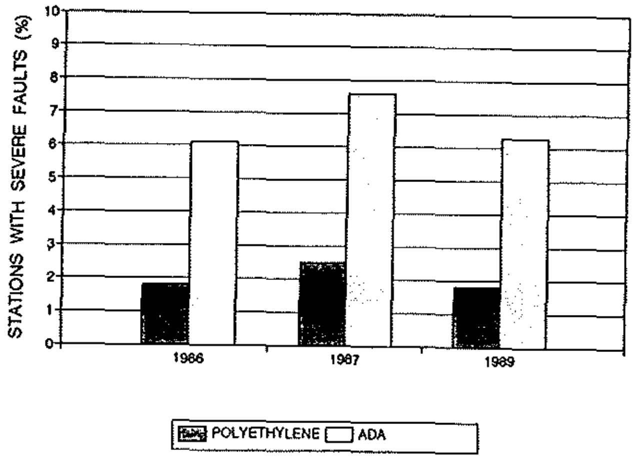

Figure 4 Continuously visible stations.

$$ac/h_{50} = \alpha + \beta(t) \tag{4}$$

where

α = initial ac/h_{50} at the start of the monitoring period,
β = slope of the regression equation, and
t = time.

If no degradation occurred, then β would equal zero, whereas a positive value would indicate an increase in leakage over time. Another statistical measure of the variation in the dependent variable (airtightness) due to the independent variable (time) is the coefficient of determination, r^2. In this application, it described the percentage of the variation in airtightness that was attributable to the time dependency. This method, using an r^2 value of 0.60, also was used to identify possible dependencies.

Table 9 summarizes the airtightness analysis using these three methods along with the results of the first and last tests on each house (expressed using ac/h_{50} data) to provide a sense of their airtightness.

PERFORMANCE OF THE CONVENTIONAL BUILDING ENVELOPE SYSTEMS

Wood Moisture Content

As shown in Table 3, the mean wall WMC levels in the two conventional houses constructed with polyethylene air barriers (9 and 10) were similar to those in the energy-efficient houses, while WMC levels in the two conventional, ADA houses (7 and 8) were slightly higher. The highest mean wall WMC values in the study were found in houses 7 and 8, mainly in walls with northern exposures.

The percentage of wall WMC readings exceeding 19% in the conventional houses was 3.4%, recorded at 2 of 16 locations in house 9, and at 6 of 16 locations in each of houses 7 and 8. Nine (out of 392) wall locations in the monitored houses were judged as having WMC levels not stable below 19%. Six of these locations were found in houses 7 and 8, even though the majority of the monitoring data (81%) was collected in the energy-efficient houses.

The WMC data were further refined to identify readings above 19% for which the wood temperature was too low to support growth of wood-rotting fungi. A temperature of 39°F (4°C) was selected as a cut-off value (Baker 1969; Hoadley 1980; Mullins and McKnight 1981). This analysis found that 35 out of 65 wall measurements above 19% in the conventional houses occurred with a wood temperature above 39°F (4°C). Expressed another way, the per-

TABLE 9 Summary of Airtightness Results

House	Monitoring Period (Months)	Air Barrier	Airtightness (ac/h_{50}) Initial	Final	Evidence of Air Barrier Degradation? Analysis Method 1	2	3
Conventional Houses							
7	36	ADA	1.17	1.42	No	No	No
8	36	ADA	1.59	1.11	No	No	No
9	36	Polyethylene	1.62	1.78	No	No	Possible
10	36	Polyethylene	1.28	1.19	No	No	No
Energy-Efficient Houses							
1	36	ADA	1.67	1.45	No	No	No
2	32	ADA	1.05	1.18	No	No	No
3	36	ADA	1.51	1.50	No	No	No
4	36	ADA	1.46	1.47	No	No	No
5	36	ADA	1.19	1.03	No	No	No
6	36	ADA	1.21	1.23	Possible	Possible	No
11	32	ADA	0.89	1.07	No	No	Possible
12	32	ADA	1.12	1.25	No	Possible	No
13	32	ADA	0.84	0.89	No	No	No
14	32	ADA	1.14	1.32	No	Possible	No
15	32	Polyethylene	1.33	1.19	No	No	No
16	32	Polyethylene	1.29	1.50	No	No	Possible
17	32	Polyethylene	0.36	0.40	No	No	No
18	32	Polyethylene	0.42	0.44	No	No	No
19	32	ADA	0.81	1.11	Possible	No	Possible
20	32	ADA	0.71	0.87	No	Possible	No
21	0.3	Polyethylene	1.83	1.84	No	—	—
22	21	Polyethylene	0.96	1.14	No	No	No
23	22	Polyethylene	1.43	1.34	No	No	No
24	19	Polyethylene	1.39	1.29	No	No	No

Analysis Method:
1. Variation between first and last airtightness tests.
2. Variation between first and last seasonally coincident airtightness tests (see note).
3. Statistical tests.

Note:
Monitoring period for Analysis Method 2 may be less than total monitoring period.

centage of wall measurements that occurred at a temperature sufficient to support fungal activity was 1.8% (35 out of 1,910). Differences also were noted in the mean wall WMC values based on wall orientation. Using data from only the fully instrumented (i.e., four-station) cavities (to ensure consistent sampling locations), the mean WMC for north walls was 13.4% vs. 10.8% for west and 9.1% for south walls.

The average predicted total air change rates during the heating season in the four conventional houses were relatively low, typically between 0.10 ACH and 0.14 ACH. Mean winter relative humidity levels were measured in houses 7 and 8 and found to be in the range of 30% to 40%, not significantly different from those in the energy-efficient houses. This suggests that the higher wall WMC levels in the conventional houses cannot be attributed to excessive interior relative humidity. In a similar vein, mechanical pressurization does not appear to have been responsible for the higher WMC levels. Houses 7 and 8 were operated in a largely balanced condition (because the ventilation systems were seldom run) so that pressure differentials across the envelopes were defined by natural forces.

The mean WMC levels in the bottom chords of the attic trusses were low and generally stable, averaging 9.1%, or 2.5% below wall levels. Only two attic measurements exceeding 19% were recorded. All attic monitoring locations were classified as stable below 19%.

Thermographic Examinations

The mean fault count for the conventional houses was relatively constant, changing from 37.0 at the beginning of the monitoring period to 35.8 at the end (all visible stations) and from 30.5 to 34.0 (continuously visible station). The percentage of locations with severe faults showed a slight increasing trend, particularly if the data for the continuously visible stations are examined—increasing from 7.6% in 1986 to 9.0% in 1989. The most common types of anomalies were air infiltration/exfiltration, interstitial air movement, or a combination of the two.

Several types of envelope construction details were found to consistently produce thermographic anomalies in the conventional houses. These are discussed in more detail in the next section because they also wereobserved in the energy-efficient houses.

Airtightness

No definitive evidence of air barrier degradation was found during the three-year monitoring period. The three methods of analysis highlighted one "possible" occurrence of degradation in house 9, but this was not judged as significant.

Performance of the Conventional Building Envelopes

Anomalies, in the form of elevated WMC levels, interstitial air movement, and air leakage, were observed with some frequency in the conventional houses. Most of these were consistent over the monitoring period. There was little evidence to suggest general degradation of the building envelope—a point illustrated by the stability of the airtightness data. However, faults will increase energy costs, reduce comfort levels, increase maintenance requirements and, perhaps most important, increase the susceptibility of conventional building envelopes to major distress when exposed to severe operating conditions such as elevated interior or exterior relative humidity levels. Also, the study houses were constructed with dry wood, which can be difficult to obtain in some areas. Further, the houses were located in a cold, dry region. Both of these are highly desirable conditions for wood frame construction.

It should be noted that "conventional" construction varies widely across North America, with conventional houses in Winnipeg being comparatively airtight and well insulated relative to those in other locations. The performance of conventional envelope systems, as defined by construction practices in other locations, may not be as satisfactory as observed in this study.

PERFORMANCE OF THE ENERGY-EFFICIENT BUILDING ENVELOPE SYSTEMS

Wood Moisture Content

The mean wall WMC levels were slightly lower in the energy-efficient houses relative to those in the conventional houses—10.3% vs. 11.6%. WMC levels in the houses constructed with polyethylene air barriers were lower than in those that used the ADA system, 9.6% vs. 10.5%. WMC levels exceeding 19% were recorded at one or more stations in house 23 (which used a polyethylene air barrier) and in ADA houses 4, 5, 6, and 12. The percentage of readings exceeding 19% was 0.3% for the energy-efficient houses as a group (24 out of 8,464). Nine out of 392 wall-monitoring locations in the project houses were judged as having WMC levels that were not stable below 19%. Only three of these were located in the energy-efficient houses (5, 6, and 23), even though 81% of the measurements were made in the energy-efficient houses.

The WMC data for the energy-efficient houses were analyzed to identify readings above 19% in which the wood temperature was too low to support fungal growth. This revealed that 19 out of 24 of the measurements above 19% occurred at temperatures above 39°F (4°C). Thus, the percentage of WMC measurements exceeding 19% in the energy-efficient houses at which the temperature was sufficient to support fungal activity was 0.2% (19 out of 8,464), compared to 1.8% for the conventional houses.

Differences in mean wall WMC values due to wall orientation were less pronounced in the energy-efficient houses. Using data from the fully instrumented cavities, north-wall WMC levels averaged 10.8%; east and west walls averaged 9.7% and 10.5%, respectively; while the mean south-wall level was 8.9%.

Six of the energy-efficient houses were instrumented with WMC pins close to various construction anomalies such as electrical outlets, etc., in anticipation of possible problems. In total, 46 sets of WMC pins were installed at these locations. None of these had readings above 19% and none of the sites was judged as not stable below 19%. Mean interior relative humidity levels during the winter ranged from 24% to 53% without apparent adverse affects. Minor window condensation problems were reported in some houses but these did not result in significant damage to the envelope.

Mean WMC levels in the attic trusses were slightly lower than those in the conventional houses and typically were 2% to 3% lower than the wall values. Observed levels in the bottom chords generally were constant over the monitoring period. Because bottom chord temperatures were fairly constant throughout the year (because they were buried in the attic insulation), this indicates the relative humidity of the air surrounding the bottom chords did not vary greatly. This suggests that appreciable moisture transport did not occur from either the house interior or the attic air to the area of the bottom chords.

Thermographic Examinations

The thermographic data indicated consistent envelope performance over the monitoring period, with no evidence of degradation being found. Using data from all visible stations, the mean fault count dropped from 35.0 in 1986 to 25.8 in 1989, while the percentage of stations with severe faults also declined. Using data from the continuously visible stations, both the fault count and the percentage of stations with severe faults changed little over the monitoring period. The energy-efficient envelopes experienced fewer thermographic anomalies than did the conventional houses. The thermographic data also showed that ceiling anomalies were less frequent and of reduced magnitude in houses that used continuous polyethylene air barriers on the ceiling (i.e., installed prior to the partition walls).

The vast majority of anomalies were categorized as either air infiltration/exfiltration or interstitial air movement. In fact, using the combined results from both the conventional and energy-efficient houses, 96% of all anomalies were attributed to these two causes (either singularly or in combination). No evidence of interstitial condensation was found in any of the thermographic inspections of the conventional or energy-efficient houses.

Stucco was used on three of the four faces of all the houses (with the exception of house 21) and, in the case of houses 11 through 20, was not installed until after the first thermographic examinations and airtightness tests had been performed. Examination of the thermographic data shows that there was a reduced incidence of anomalies along the floor line in some of the ADA houses after the stucco had been installed, possibly indicating a reduction in air leakage in this region.

Airtightness

The airtightness analysis identified nine occurrences of possible, albeit slight, evidence of airtightness degradation in the 20 energy-efficient houses. However, the magnitude of these changes was small and they were not judged to be of practical significance. It was concluded that no definitive evidence could be found of air barrier degradation in the energy-efficient houses. It was further concluded that no evidence was found to indicate that either the polyethylene or ADA systems were unsuited for use in residential construction.

Performance of the Energy-Efficient Building Envelopes

Mean wall and attic WMC levels were lower and more stable in the energy-efficient houses compared to the conventional houses. In addition, fewer instances were found of WMC levels exceeding 19%, and a smaller percentage of monitoring locations was judged as not being stable below 19%. The energy-efficient houses also demonstrated a lower incidence of thermographic anomalies, particularly those of a severe nature. Airtightness tests showed that leakage rates were lower in the energy-efficient houses, especially those using the double-wall system.

No evidence was found of envelope degradation in any of the energy-efficient houses. Both the polyethylene and ADA houses demonstrated predominantly stable WMC levels and thermographic characteristics. Airtightness rates were basically stable over the three-year monitoring period, indicating that the integrity of the air barriers had been maintained.

No significant evidence was found of elevated moisture levels in the energy-efficient houses. Houses constructed with high levels of cavity insulation in the exterior walls and attic areas did not demonstrate an unusual incidence of problems. Houses constructed with sandwiched air/vapor polyethylene barriers (double walls and strapped walls) did not display elevated WMC levels or evidence of interstitial condensation.

Building envelopes that used polyethylene air barriers generally performed slightly better than those built using the ADA system, although both functioned in a satisfactory manner. WMC levels were a little lower in the polyethylene houses, and the mean thermographic fault counts and the percentage of monitoring stations with severe faults also was lower in the polyethylene houses. Both types of construction demonstrated stable airtightness rates.

Finally, it should be recognized that the ADA houses were constructed using early versions of the system. Since then, many changes—specifically in the types of materials used for gaskets—have improved the durability and performance of the ADA system.

Problem Details

Several types of construction details consistently produced thermographic anomalies in both the energy-efficient and conventional houses:

(a) Bow window framing—The thermal images suggested an interaction, in the form of interstitial air movement, between the main wall and the window framing. In many ADA houses, the anomalies were strongest at the base of the wall along the floor, indicating leakage past the bottom gasket.

(b) Vertical walls exposed to attics on one side—Several houses were constructed with both vaulted and flat (truss) ceilings, which required a connecting vertical wall between the two. These walls displayed massive thermal anomalies over most or all of their surfaces, which was categorized as interstitial air movement. The cause was attributed to slight separation of the batt insulation from the wall (due to the absence of exterior sheathing on the attic side), which permitted air movement between the insulation and the drywall.

(c) Plumbing walls—In many cases, particularly in the ADA houses, significant interstitial air movement was observed on one or both sides of the wall, generally in the vicinity of the plumbing stack. This anomaly may have been caused by air leakage around the plumbing stack due to inadequate sealing at the top plate.

(d) Exterior doors/entrance ways—Interstitial air movement was frequently noted in the exterior wall in the vicinity of the entrance door, typically near low divider walls that intersected the exterior wall near the door. Faults were observed with all wall construction types, including the double walls.

Because these anomalies were found in many houses, they cannot be attributed to faulty workmanship or poor materials. They represent systematic faults that can be expected to occur whenever such details are used.

CONCLUSIONS

1. The energy-efficient building envelope systems performed better than those constructed with conventional construction techniques. Wall and attic WMC levels were lower, and fewer excursions above 19% were recorded. The energy-efficient houses also demonstrated fewer thermographic anomalies, particularly those of a severe nature. No evidence of interstitial condensation was found in either the conventional or energy-efficient envelopes. Air leakage rates were lower in the energy-efficient houses.
2. No evidence of envelope degradation was found in any of the energy-efficient houses. Both the polyethylene and ADA houses demonstrated predominantly stable WMC levels, thermographic characteristics, and airtightness rates over the three-year monitoring period. No significant evidence was found of elevated moisture levels in the energy-efficient houses. Houses constructed with high levels of cavity insulation in the exterior walls and attics did not display an unusual incidence of problems, elevated WMC levels, or evidence of interstitial condensation. These results also demonstrated the benefits of using dry wood and a low leakage air barrier.
3. The building envelopes constructed using polyethylene air barriers performed slightly better than those that used ADA, although both were judged as satisfactory. WMC levels were a little lower in the polyethylene houses, while the mean thermographic fault counts and the percentage of monitoring stations with severe faults were less in the polyethylene houses.
4. Several types of construction details consistently produced thermographic anomalies in both the energy-efficient and conventional houses: (a) wall framing around bow windows, (b) vertical walls exposed to attic air on the cold side (i.e., sections joining truss ceilings with vaulted ceilings), (c) interior plumbing walls, and (d) wall framing around exterior doors/entrance ways.

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