FIELD PERFORMANCE OF ENERGY-EFFICIENT RESIDENTIAL BUILDING ENVELOPE SYSTEMS

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SUMMARY

A three year field study of 20 energy efficient houses and four conventional dwellings was conducted to evaluate the performance of their building envelope systems. Ten of the houses were built with polyethylene air barriers and 14 using the Airtight Drywall Approach (ADA). All were newly constructed and used dry wood for the framing members, i.e. with a wood moisture content (WMC) below 19%. The project took place in Winnipeg, Manitoba - a region with a cold, dry climate.

Building envelope performance was evaluated by developing a comprehensive monitoring program which included measurements of wall, attic and floor joist WMC levels, detailed thermographic examinations and regular airtightness testing. Over 13,000 WMC measurements were performed, 1013 thermographic images recorded and 167 airtightness tests conducted.

PERFORMANCE OF ENERGY EFFICIENT vs. CONVENTIONAL BUILDING ENVELOPE SYSTEMS

Both the energy efficient and conventional building envelope systems performed in a satisfactory manner although fewer problems were found in the energy efficient houses. Lower mean WMC levels were measured in the walls and attics and fewer WMC excursions above 19% 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. The energy efficient houses were also found to be more airtight than the conventional structures.

DEGRADATION OF THE ENERGY EFFICIENT BUILDING ENVELOPES

No evidence of envelope degradation was found in the energy efficient houses. Both the polyethylene air barrier houses and those built using the ADA system demonstrated predominately stable WMC levels, thermographic characteristics and airtightness over the three year monitoring period.

EVIDENCE OF ELEVATED MOISTURE LEVELS IN THE ENERGY EFFICIENT HOUSE ENVELOPES

No significant evidence was found of elevated WMC levels in the energy efficient houses. Houses constructed with high levels of insulation in the exterior walls, attics and floor joist/header areas did not display an unusual incidence of problems, elevated WMC levels or evidence of interstitial condensation. This included a group of houses which were constructed with sandwiched polyethylene air/vapour barriers (i.e. double walls and frame walls with interior strapping). These results were also interpreted as a demonstration of the benefits of using dry wood for construction and of incorporating a low leakage air barrier in the design of the building envelope.

POLYETHYLENE AIR BARRIERS vs. THE AIRTIGHT DRYWALL APPROACH

The building envelopes constructed using polyethylene air barriers generally performed in a superior fashion to those which used ADA, although both systems provided satisfactory performance. WMC levels were slightly lower in the polyethylene houses as were the number of thermographic faults, particularly those of a severe nature.

PROBLEM DETAILS

Several types of construction details consistently produced thermographic anomalies in both the energy efficient and conventional houses. The most significant were: a) the wall framing around bow windows (particularly in ADA construction at the wall/floor interface), b) vertical walls exposed to attic air on the cold side (i.e. sections joining horizontal ceilings with vaulted ceilings), c) interior plumbing walls and d) the wall framing around exterior doors/entrance ways. Possible explanations were suggested for each anomaly.

This study was conducted as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project.

RÉSUMÉ

Une étude sur le terrain de trois ans, visant à évaluer le rendement des systèmes d'enveloppe du bâtiment, a été menée sur 20 maisons éconergétiques et sur quatre logements classiques. Dix (10) des maisons avaient été construites avec pare-air en polyéthylène et 14, suivant la méthode des murs secs étanches à l'air. Toutes étaient de construction récente et comportaient des éléments de charpente en bois sec, c'est-à-dire un bois ayant un degré d'humidité inférieur à 19 %. Le projet a été réalisé à Winnipeg, Manitoba, une région au climat froid et sec.

Le rendement de l'enveloppe du bâtiment a pu être évalué grâce à la mise au point d'un programme de contrôle exhaustif, qui comprenait des mesures de degré d'humidité du bois des murs, du vide sous toit et des solives de plancher, des examens thermographiques détaillés et l'essai habituel d'étanchéité à l'air. Plus de 13 000 mesures du degré d'humidité du bois ont été relevées, 1 013 images thermographiques enregistrées et 167 essais d'étanchéité à l'air effectués.

ÉVALUATION COMPARATIVE DES SYSTÈMES D'ENVELOPPE DU BÂTIMENT À HAUT RENDEMENT ÉNERGÉTIQUE ET DES SYSTÈMES CLASSIQUES

Les systèmes d'enveloppe du bâtiment à haut rendement énergétique tout comme les systèmes classiques se sont comportés de manière satisfaisante, bien que moins de problèmes aient été relevés dans les maisons éconergétiques. Des degrés d'humidité moyens du bois dans les murs et les vides sous toit ont été relevés et un moins grand nombre d'écarts des degrés d'humidité du bois au delà de 19 % a été enregistré. Les maisons éconergétiques ont également présenté moins d'anomalies thermographiques, plus particulièrement celles de nature grave. Aucun signe de condensation interne n'a été constaté dans l'un ou l'autre type de construction. Les maisons éconergétiques se sont également avérées plus étanches à l'air que les constructions classiques.

DÉGRADATION DES ENVELOPPES DU BÂTIMENT À HAUT RENDEMENT ÉNERGÉTIQUE

Aucun signe de dégradation de l'enveloppe n'a été relevé dans les maisons éconergétiques. Dans les maisons étanchéisées à l'aide de polyéthylène ainsi que dans celles construites suivant la méthode des murs secs étanches à l'air, les niveaux d'humidité du bois, les caractéristiques thermographiques et l'étanchéité à l'air se sont avérés stables d'une manière prédominante au cours de la période de contrôle de trois ans.

NIVEAUX D'HUMIDITÉ DANS LES ENVELOPPES DU BÂTIMENT À HAUT RENDEMENT ÉNERGÉTIQUE

Aucune preuve de niveaux d'humidité élevés du bois n'a été constatée dans les maisons éconergétiques. Les maisons construites avec niveau d'isolation élevé dans les murs extérieurs, les vides sous toit et les zones de solives de plancher/linteaux n'ont pas présenté d'incidence anormale de problèmes, de niveaux d'humidité du bois élevés ni de signes de condensation interne. Ceci comprenait un groupe de maisons construites avec pare-air/vapeur en polyéthylène doubles (soit des murs doubles et des murs à ossature (doubles) avec fourrure intérieure). Ces résultats ont également été interprétés comme une démonstration des avantages de l'utilisation de murs secs pour la construction et de l'incorporation dans la conception de l'enveloppe du bâtiment de pare-air à faible taux d'infiltration et d'exfiltration.

PARE-AIR EN POLYÉTHYLÈNE ET MÉTHODE DES MURS SECS ÉTANCHES À L'AIR

Les enveloppes du bâtiment construites à l'aide de pare-air en polyéthylène se sont généralement mieux comportées que celles qui utilisaient la méthode des murs secs étanches à l'air, bien que les deux systèmes aient donné un rendement satisfaisant. Les degrés d'humidité du bois étaient légèrement inférieurs dans les maisons munies de polyéthylène, de même que le nombre de défauts thermographiques, plus particulièrement ceux de nature grave.

DÉTAILS PROBLÉMATIQUES

Plusieurs types de détails de construction ont produit régulièrement des anomalies thermographiques, tant dans les maisons éconergétiques que dans les maisons de type classique. Parmi les plus importants, mentionnons: a) l'ossature du mur autour des oriels (particulièrement dans les constructions à murs secs étanches à l'air à l'interface mur-plancher; b) des murs verticaux exposés à l'air du vide sous toit, du côté froid (soit les sections reliant les plafonds horizontaux aux plafonds en voûte); c) les murs de plomberie intérieurs et d), l'ossature du mur, autour des entrées de porte extérieures. Des explications possibles ont été proposées pour chaque anomalie.

Cette étude a été réalisée dans le cadre du Projet de démonstration de la maison à haut rendement énergétique/Mark XIV de l'ACCH, de Flair Homes.

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SECTION 1

INTRODUCTION

1.1 THE BUILDING ENVELOPE

The purpose of the building envelope is to provide protection from cold, heat, moisture, wind and noise by establishing a separation between the indoor and outdoor environments. Since the envelope is subject to a continuing array of thermal, structural and moisture stresses, its performance can degrade over time. This may result in localized or general failure of the structure unless extensive repairs are carried out. Performance of the envelope is obviously critical to successful building operation.

During the last decade, concerns have been expressed about the adequacy and durability of residential building envelopes constructed with high levels of thermal insulation and well-sealed air/vapour barriers. These concerns have increased with the development of alternative methods of providing air and vapour barrier protection for which there is comparatively limited experience, such as the Airtight Drywall Approach (ADA).

1.2 OBJECTIVES

To overall purpose of this study was to evaluate the performance of various types of energy efficient residential building envelope systems. The specific objectives were:

1. To compare the performance of energy efficient building envelope systems relative to those built using conventional methods.

2. To look for degradation in envelope performance which might occur during the first few years of occupancy.

3. To investigate whether unacceptably high moisture levels are encountered in the building envelopes of energy efficient houses.

4. To compare the performance of envelope systems constructed using polyethylene air barriers with those employing the Airtight Drywall Approach.

1.3 SCOPE

The study was restricted to a field evaluation of new houses constructed in a single geographic, and hence climatic, region - Winnipeg. House type and size were intentionally kept similar while workmanship and materials quality were representative of local industry standards. Some variation in operating conditions was accepted because the houses were privately owned and operated.

1.4 THE FLAIR HOMES ENERGY DEMO/CHBA FLAIR MARK XIV PROJECT

The work described in this report was conducted as part of the Flair Homes Energy Demo/CHBA Flair Mark XIV Project. This project was created in 1985 to provide a demonstration of various energy conservation technologies, products and systems which might be suitable for the Canadian home building industry. The specific objectives of the project were:

1. To demonstrate and evaluate the performance of various low energy building envelope systems.

2. To demonstrate and evaluate the performance of various space heating, hot water heating and mechanical ventilation systems.

3. To transfer the knowledge gained in the project to the Canadian home building industry.

Support for the project was provided by Energy, Mines and Resources Canada under the Energy Demo Program and by Manitoba Energy and Mines under the Manitoba/Canada Conservation and Renewable Energy Demonstration Agreement (CREDA). Project management was the responsibility of Flair Homes (Manitoba) Ltd. Project monitoring and reporting were performed by UNIES Ltd., consulting engineers, of Winnipeg.

The project was also designed to provide technical support to the R-2000 Home Program, which is funded by Energy, Mines and Resources Canada and administered by the Canadian Home Builders Association (CHBA). The CHBA's "Mark XIV" designation was acquired when a major portion of the research priorities identified by the CHBA's Technical Research Committee was incorporated into the work plan.

To meet the project's objectives, 24 houses were constructed in Winnipeg by Flair Homes Ltd. and independently monitored for periods of up to three years. Energy conservation levels ranged from those of conventional houses to those which met or exceeded the R-2000 Standard.

1.5 REPORT ORGANIZATION

Sections 1 to 6 describe the scope and objectives of the study and detail the monitoring program and evaluation methods used to assess the performance of the building envelope systems. Section 7 discusses the performance of the building envelopes in the conventional houses while Section 8 reviews envelope performance in the energy efficient houses. Section 9 contains the conclusions and recommendations.

SECTION 2

DESCRIPTION OF THE MONITORING PROGRAM

2.1 OVERVIEW

The monitoring program consisted of a three year field study of 20 energy efficient and four conventional houses built between 1985 and 1989 by Flair Homes (Manitoba) Ltd., a large Winnipeg tract builder. The conventional houses were included to provide a performance benchmark for the energy efficient structures.

The 24 houses were all standard, detached bungalows with full basements. Two floor plans with (interior) main floor areas of 60 m^2 and 85 m^2 (646 ft^2 and 915 ft^2) were used. All but one of the houses were privately owned and occupied. Brief summaries, complete with descriptions of the air and vapour barriers, are provided in Tables 1 and 2. More detailed descriptions are given in Proskiw (1992).

2.2 CONVENTIONAL vs. ENERGY EFFICIENT BUILDING ENVELOPE SYSTEMS

There is no commonly agreed upon classification system to distinguish conventional from energy efficient construction, therefore a method was developed which defined an energy efficient envelope as one which possessed:

1. High levels of thermal insulation and
2. A well-sealed air barrier.

Since the 24 houses were constructed with insulation levels comparable to, or exceeding, those found in local R-2000 houses, the main criterion used in this study for classifying the envelope systems was the type of air barrier. For this purpose, a well-sealed air barrier was defined as one which was a) carefully sealed during construction and b) able to consistently meet the R-2000 airtightness requirements.

Using this criterion, four of the project houses were categorized as conventional (#7 to #10) and the remaining 20 as energy efficient although the distinction between these two classes is not clear-cut. The four conventional houses demonstrated air leakage rates at or near those specified for R-2000 houses; they were classified as conventional because of occasional excursions above the R-2000 airtightness limit (#7 and #8) or because they did not contain a sealed air barrier and relied on other envelope components, such as stucco, to achieve their final airtightness (#9 and #10).

TABLE 1
DESCRIPTION OF PROJECT HOUSES

Feb/92

HOUSE	BUILDING ENVELOPE					MECHANICAL SYSTEMS		YEAR COMPLETED	ENERGY STANDARD
	WALL CONSTRUCTION	EXTERIOR WALL FINISH	BASEMENT CONSTRUCTION	CEILING/ATTIC CONSTRUCTION	WINDOWS	SPACE HEATING SYSTEM	VENTILATION SYSTEM		
1-6	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing (Reversed) c/w SBPO Air Retarder	Stucco with Wood or Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Heat Recovery Ventilator	1985	R-2000
7,8	38x140 (2x6)	Stucco with Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Forced Air Furnace	Central Exhaust with Make-Up Air Duct	1985	Conventional
9,10	38x140 (2x6)	Stucco with Stone & Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Gas Forced Air Furnace	Bathroom Exhaust Fan	1985	Conventional
11-14	38x140 (2x6), Rigid Glass Fibre Insulated Sheathing c/w SBPO Air Retarder	Stucco with Wood, Brick or Stone Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & 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 & 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 & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
19,20	38x89 (2x4), Rigid Extruded Polystyrene Sheathing	Stucco with Wood & Brick Siding	Cast Concrete	Truss Ceiling	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards	Heat Recovery Ventilator	1986	R-2000
21	Predominately 38x140 (2x6) with Interior Strapping	Vinyl & Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Several Types	Several Types	Several Types	1989	R-2000
22	38x140 (2x6)	Stucco with Wood & Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed & Awning	Electric Forced Air Furnace	Central Exhaust	1988	Conventional
23	38x140 (2x6) with Interior Strapping	Stucco with Wood Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed & Awning	Electric Forced Air Furnace	Heat Recovery Ventilator	1988	R-2000
24	38x140 (2x6) with Extruded Polystyrene Sheathing	Stucco with Wood & Brick Siding	Cast Concrete	Cathedral & Truss Ceilings	Triple-Glazed; Fixed, Awning & Casement	Electric Baseboards & Radiant Panels	Heat Recovery Ventilator	1988	R-2000

TABLE 2
AIR AND VAPOUR BARRIER DETAILS

Feb/92

HOUSE	AIR BARRIER							VAPOUR BARRIER		
	TYPE	SEALING METHOD					CREW	WALLS	CEILING	BASEMENT
		HEADERS	CANTILEVERS	PARTITION WALLS AT CEILING	WINDOW & DOOR ROUGH OPENINGS	ELECTRICAL OUTLETS				
1-6	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes & Gaskets	A	Paint	Paint	Paint
7,8	ADA	Closed Cell Polyethylene Gaskets	Closed Cell Polyethylene Gaskets	Gaskets	Gaskets	Poly-Pan Boxes & Gaskets	A	Paint	Paint	Paint
9,10	4 mil Polyethylene	None	None	Unsealed Polyethylene	Unsealed Polyethylene	Unsealed Polyethylene	A	Polyethylene	Polyethylene	Polyethylene
11-14	Simplified ADA	None	None	None	Ethafoam Rod Gaskets	Poly-Pan Boxes & Gaskets	B	Paint	Paint	Paint
15,16	6 mil Polyethylene	Caulking	Caulking	Sealed Polyethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyethylene	Polyethylene	Polyethylene
17,18	6 mil Polyethylene	Caulking	Caulking	Sealed Polyethylene	Sealed Polyethylene	Sealed Polyethylene	B	Polyethylene	Polyethylene	Polyethylene
19,20	ADA	Closed Cell Polyethylene & Neoprene Gaskets	Closed Cell Polyethylene & Neoprene Gaskets	Neoprene Gaskets	Ethafoam Rod Gaskets	Poly-Pan Boxes & Gaskets	B	Paint	Paint	Paint
21	Primarily 6 mil Polyethylene	Sealed Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene	Various	Sealed Polyethylene	C	Polyethylene	Polyethylene	Polyethylene
22	Primarily 6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyethylene	Polyethylene	Polyethylene
23	6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene	Various	Sealed Polyethylene	D	Polyethylene	Polyethylene	Polyethylene
24	6 mil Polyethylene	Sealed Polyethylene & SBPO Air Retarder	Sealed Polyethylene & SBPO Air Retarder	Saturated Urethane Open Cell Gaskets	Various	Polyethylene	D	Polyethylene	Polyethylene	Polyethylene

2.3 DESCRIPTION OF THE WALL SYSTEMS

The four conventional houses (#7 to #10) were constructed with standard 38x140 (2x6) frame walls while the 20 energy efficient houses were built using four types of wall systems:

- o Standard frame walls (#22),
- o Frame walls with exterior insulated sheathing (#1 to #6, #11 to #14, #19, #20 and #24),
- o Frame walls with interior strapping (#21 and #23) and
- o Double wall construction (#15 to #18).

Each house was constructed using either a polyethylene air/vapour barrier or the Airtight Drywall Approach (ADA).

2.4 EVALUATION METHODS

Building envelope performance was evaluated by developing a comprehensive monitoring program comprising:

1. Regular measurement of the wood moisture content (WMC) of wall, roof truss and floor joist framing members,
2. Periodic thermographic examinations of the house interiors and
3. Periodic airtightness tests of each structure.

The monitoring schedule is summarized in Table 3 (a, b and c).

The three evaluation methods were selected because of the complementary information which they provided. For example, the WMC data supplied precise information on framing member performance at the discrete locations where the probes were installed (discussed in Section 3). However, this knowledge of wood behaviour at specific locations did not provide average or overall performance data for other parts of the envelope. This problem was minimized by the use of large numbers of WMC probes and the inclusion of monitoring locations in high threat areas of the envelope. In contrast, the thermographic examinations "sampled" most of the envelope area but had the disadvantage of viewing only surface conditions, i.e. the method was less sensitive to conditions within the interior of the envelope, particularly on the cold side where the maximum moisture stresses usually occur. Finally, the airtightness test results provided data on the performance of the entire envelope and in particular the air barrier.

2.5 ADDITIONAL INFORMATION

Additional information was collected to permit determination of mechanical ventilation rates, natural air infiltration rates, envelope pressurization created by mechanical ventilation systems, indoor air temperatures and relative humidity. Questionnaires were also administered to the homeowners on a regular basis.

TABLE 3(a)

WOOD MOISTURE CONTENT MEASUREMENT SCHEDULE (READINGS TAKEN MONTHLY)

HOUSE	WALLS	ATTIC	FLOOR JOISTS
1	APR/86-MAR/89	APR/86-MAR/89	
2	APR/86-MAR/89	APR/86-MAR/89	
3	MAY/86-MAR/89	MAY/86-MAR/89	
4	MAY/86-FEB/89	MAY/86-FEB/89	
5	MAY/86-FEB/89	MAY/86-FEB/89	
6	MAY/86-FEB/89	MAY/86-FEB/89	
7	APR/86-MAR/89	APR/86-MAR/89	
8	APR/86-MAR/89	APR/86-MAR/89	
9	APR/86-MAR/89	APR/86-MAR/89	
10	APR/86-MAR/89	APR/86-MAR/89	
11	AUG/86-MAR/89	AUG/86-MAR/89	
12	JUL/86-MAR/89	JUL/86-MAR/89	
13			
14			
15	OCT/86-FEB/89	OCT/86-FEB/89	
16	MAY/86-FEB/89	MAY/86-FEB/89	
17			
18			AUG/86-MAR/89
19	MAY/86-MAR/89	MAY/86-MAR/89	
20	AUG/86-MAR/89	AUG/86-MAR/89	AUG/86-MAR/89
21			
22			
23	NOV/88-APR/90		
24			

TABLE 3(b)

THERMOGRAPHY SCHEDULE

HOUSE	MAR/86	FEB/87	MAR/89
1	X	X	X
2	X	X	X
3	X	X	X
4	X	X	X
5	X	X	X
6	X	X	X
7	X	X	X
8	X	X	X
9	X	X	X
10	X	X	X
11	X	X	X
12	X	X	X
13	X	X	X
14	X	X	X
15	X	X	X
16	X	X	X
17	X	X	X
18	X	X	X
19	X	X	X
20	X	X	X
21			
22			
23			
24			

TABLE 3(c)
AIRTIGHTNESS TEST SCHEDULE

HOUSE	MAR/86	JUL/86	NOV/86	FEB/87	JUL/87	NOV/87	FEB/88	MAY/88	JUN/88	JUL/88	AUG/88	NOV/88	MAR/89	JUN/89	AUG/89	DEC/89	JAN/90	MAR/90	APR/90
1	X		X	X			X					X	X						
2		X	X	X	X	X	X			X		X	X						
3	X		X	X	X		X						X						
4	X		X	X	X		X			X			X						
5	X		X	X	X		X						X						
6	X		X	X	X		X			X			X						
7	X		X	X						X			X						
8	X		X	X	X		X			X			X						
9	X	X	X	X	X	X	X			X		X	X						
10	X	X	X	X	X	X	X			X		X	X						
11	X	X	X	X	X		X						X						
12	X	X	X	X	X		X			X			X						
13	X	X	X	X	X		X			X			X						
14	X	X		X	X		X			X			X						
15	X	X	X	X			X			X			X						
16	X	X	X	X			X						X						
17	X	X	X	X	X	X	X			X		X	X						
18	X	X	X	X	X	X	X			X		X	X						
19	X	X	X	X	X		X			X			X						
20	X	X	X	X	X		X			X			X						
21																	X		
22								X		X						X			X
23								X	X					X		X			X
24											X				X	X		X	

2.6 THE WINNIPEG CLIMATE

The performance of a building envelope is intimately tied to the climate in which it is located. Winnipeg's climate can be described as cold and dry with a relatively severe winter compared to other Canadian cities. It experiences 5923 heating degree days per year and has a 97.5% design temperature of -33 °C (-27 °F). Precipitation averages 52.6 cm (21") per year and summer daytime relative humidity levels are typically in the range of 30% to 60%.

SECTION 3

WOOD MOISTURE CONTENT

3.1 WOOD, MOISTURE AND DECAY

"Except for structural errors, about 90% of all building construction problems are associated with water in some way" (ASTM 1982).

Understanding the interaction between moisture and the building envelope, particularly wood components, is critical to the development of a sound knowledge base on house performance. The wood moisture content is defined as the weight of water contained in a wood sample and is expressed as a percentage of its oven-dry weight. In living trees, the moisture content may range from about 30% to over 200%. Lumber used for residential construction is required, under Article 9.3.2.5 of the National Building Code (NBC), to have a moisture content which does not exceed 19% at the time of installation (1990). Wood with a WMC of 19% or less is generally considered as "dry".

Wood is a hygroscopic material, i.e. it will absorb or release moisture in response to changes in the relative humidity of the surrounding air. Given sufficient time and stable environmental conditions, it will achieve a condition at which its moisture content will remain constant, referred to as the "Equilibrium Moisture Content". From a construction perspective, the moisture content of wood is critical for two reasons: dimensional stability and susceptibility to decay.

Variations in the WMC can cause wood to undergo significant dimensional changes particularly in the tangential and radial directions (relative to grain direction). A classic example of damage resulting from fluctuations in the WMC is truss uplift in which the upper and the lower chords of the truss, which are generally exposed to different relative humidity levels, expand or shrink differentially resulting in an upward bowing of the bottom chord. Many other problems, such as drywall nail popping, floor squeaks, etc. can also be attributed to dimensional instability. These have a major impact on the home building industry in the form of customer dissatisfaction and increased warranty claims.

Since wood is an organic material, it is susceptible to fungal decay. For decay to take place, five conditions must be satisfied: a source of oxygen must be present (e.g. ambient air), the temperature must be between approximately 4 °C and 41 °C (40 °F to 105 °F), a food source must be present (the wood), a source of infection must exist (usually available from airborne spores) and finally, moisture must be present. The optimum moisture content for fungal growth is around 30%. Wood at the NBC level of 19% or less is generally considered safe from most types of fungal attack. The precise threat which exists with WMC levels in the

19% to 30% range has not been clearly defined but is believed to be non-linear with only a minimal threat in the 19% to 22% range.

Under ideal circumstances, the WMC of wood members should be maintained below 19% to minimize the potential for wood decay. If the WMC does exceed 19%, it should preferably occur when the wood temperature is too low for effective fungal growth. This determination of decay potential is an arbitrary, but reasoned criterion and is useful of making comparisons. However it should not be implied that framing members which experience instances over the criterion are necessarily at risk. It has been observed that even when a source of infection has been provided and conditions appear optimal, it is sometimes difficult to initiate decay (Onysko 1992).

3.2 METHODOLOGY

Framing member wood moisture content was monitored in 18 of the 24 houses using permanently installed moisture pins embedded at various locations in the walls, roof trusses and floor joists. In total, 516 sets of pins were installed at the time of construction and the moisture content measured roughly once per month during regular site visits. In excess of 13,000 monthly WMC measurements were made during the project. The locations and distribution of WMC monitoring pins are summarized in Table 4.

Wood moisture content measurements were made using a Delmhorst G-30 meter connected through a switch box to the moisture pins. To minimize extraneous electromagnetic interference, a shielding system was installed in each house which allowed the metal stucco wire to be electrically grounded when measurements were being conducted.

3.2.1. Wall Cavities

A typical instrumented wall cavity, shown in Fig. 1., contained 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, 6 mm (¼") below the surface, while the second recorded the mid-depth (core) moisture content. A thermocouple was installed between the two sets of pins along a common isotherm to permit temperature corrections to be applied to the meter readings. All moisture pins were installed parallel to the wood grain. Most cavities were instrumented with four stations, two on the stud and one on each of the top and bottom plates. The stud stations were located 25 mm (1") from the warm and cold faces respectively while the plate stations were both located 25 mm (1") from the cold faces. Station positions were selected to avoid knotholes, nails and other obvious anomalies. The installing technician was also responsible for insulating the cavity to insure the pins and leads were not damaged by subsequent tradesmen. Instrument cables were soldered to each set of pins and then routed, along with the thermocouple lines to a central location in the basement where they were

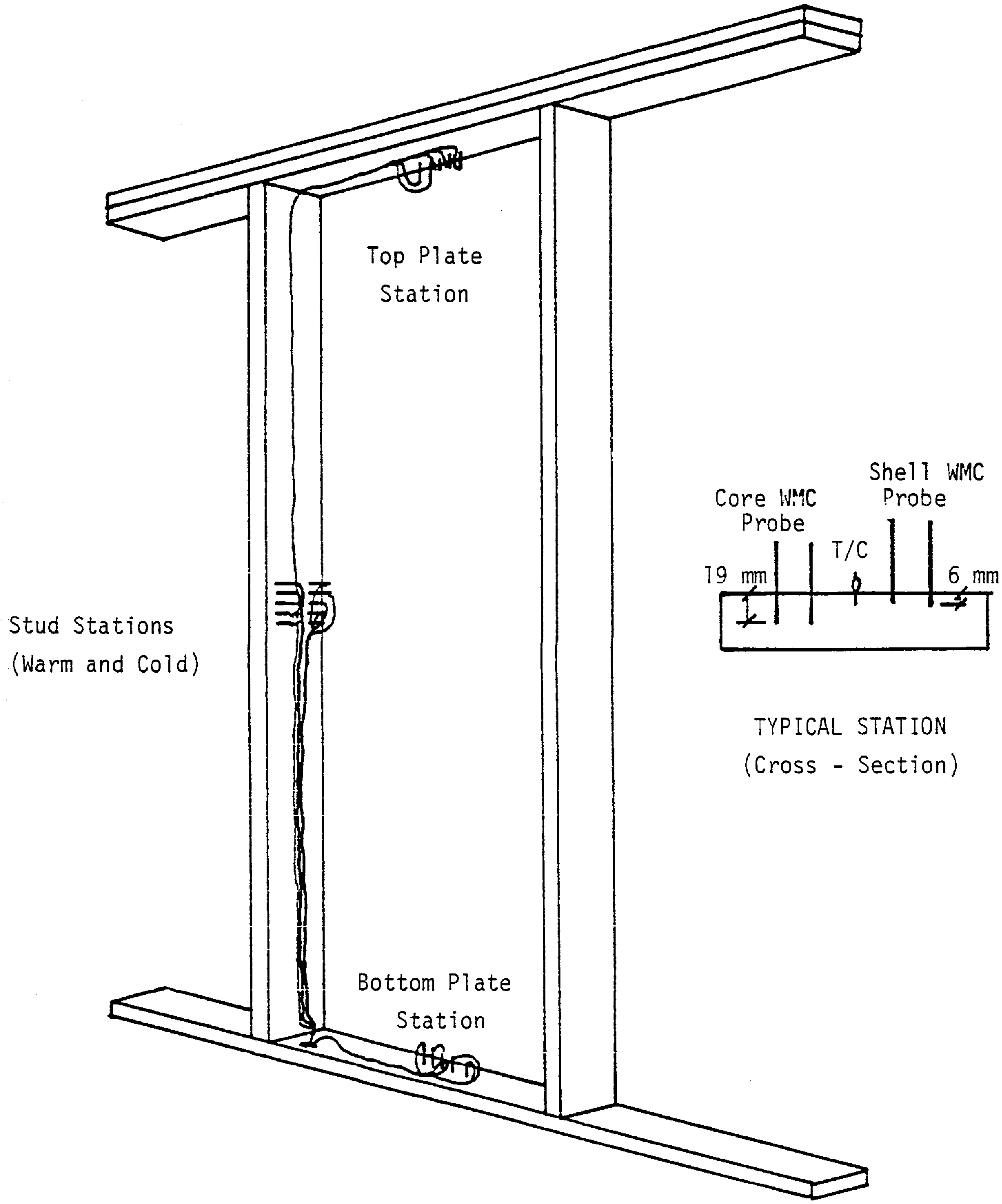
TABLE 4

WOOD MOISTURE CONTENT (WMC) MONITORING LOCATIONS

HOUSE	WALLS								ATTICS		FLOOR JOISTS
	FULL CAVITY				PARTIAL CAVITY OR ON STRAPPING				BOTTOM CHORD	TOP CHORD	
	N	E	W	S	N	E	W	S			
1	1			1					1		
2	1		1						1		
3	1		1						1		
4	1	1							1		
5	1		1		1				1		
6	1		1			1			1		
7	1		1						1		
8	1			1					1		
9	1			1					1		
10	1		1						1		
11	1	1	1		1	4			1	1	
12	1		1		1	4			1	1	
13											
14											
15	1	1		1	1	1			1	1	
16	1	1		1	1	1			1	1	
17											
18											10
19	1	1	1		1	3			1	1	
20	1	1	1		1	4			1	1	10
21											
22											
23	1	1			1	1	2				
24											

NOTES:

1. FULL CAVITY: Cavity contained four sets of WMC pins (two on studs and two on plates).
2. PARTIAL CAVITY: Cavity contained less than four sets of WMC pins.
3. STRAPPING: House #23 only, interior strapping instrumented with WMC pins.



TYPICAL WALL CAVITY WMC INSTRUMENTATION

FIGURE 1

terminated on quick-disconnect, multi-pin plugs. Cable bundles were routed to minimize temperature distortions to the sampling locations.

Additional monitoring stations were installed in several wall cavities containing construction anomalies, such as windows, electrical outlets and corner framing. One of the houses, which was constructed with interior strapping on the main walls (#23), was also instrumented with WMC pins on the strapping.

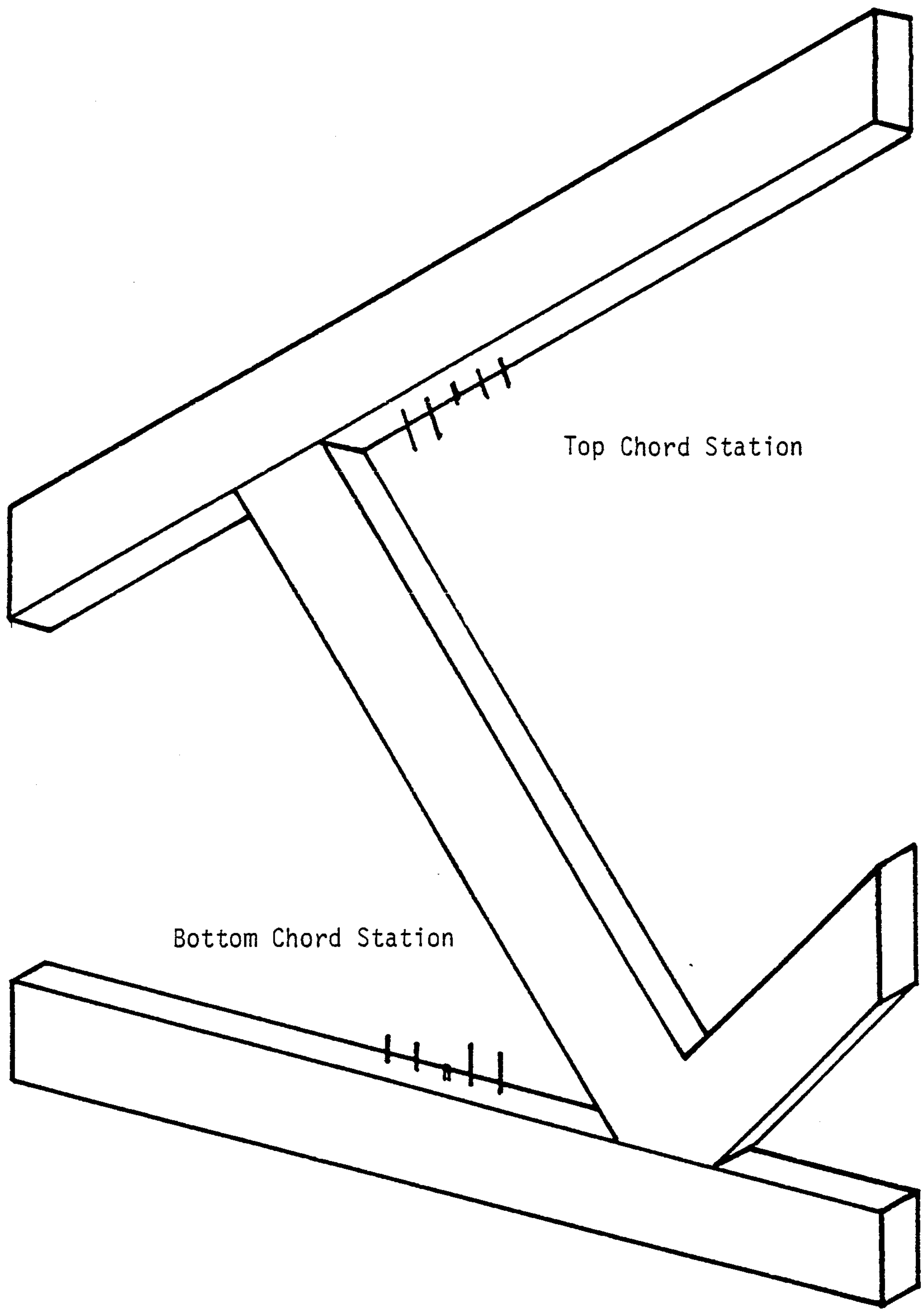
3.2.1 Roof Trusses

Wood moisture monitoring stations were installed on the top and bottom chords of the roof trusses in several houses. A typical installation is shown in Fig. 2.

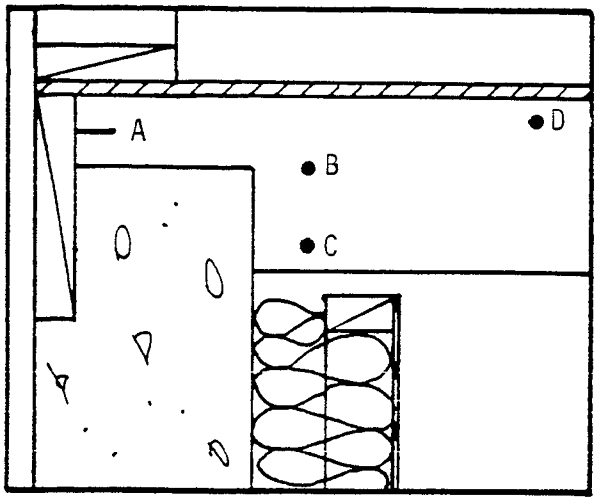
3.2.2. Floor Joists

Concerns have been expressed that floor joists embedded in solid masonry walls may be susceptible to wood decay when interior insulation is used in conjunction with a tight-fitting polyethylene membrane on the interior (EMR 1985). Under summer conditions, moisture absorbed from the outdoors (due to capillary transport from the soil, rain or sprinkler action against the above-grade portion of the foundation, etc.), can only escape from the wall by a process of capillary action and diffusion to the outdoors. If the interior surface is insulated and sealed to prevent vapour diffusion, the moisture conditions in the masonry wall near the embedded joist ends may be sufficient to induce wood decay in the joists. Because of the similarity of this method of construction to concrete basements which use cast-in-place floor joists/ headers, two houses (#18 and #20) were constructed using five different floor joist/header insulation systems and air/vapour barrier techniques as shown in Fig. 3. House #18 used interior basement insulation while House #20 was built with exterior extruded polystyrene insulation plus interior insulation. The floor joist/header insulation schemes consisted of:

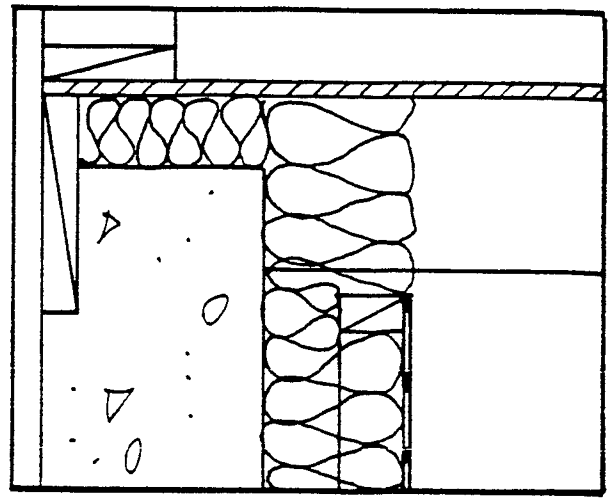
- Type 1 Open floor joist cavity, no insulation, no air or vapour barriers.
- Type 2 Glass fibre batts in the floor joist cavity, no air barrier, no vapour barrier.
- Type 3 Glass fibre batts in the floor joist cavity, no air barrier, loosely installed 6 mil polyethylene vapour barrier.
- Type 4 No insulation, airtight air barrier (caulked-in-place plywood) which also formed the vapour barrier.
- Type 5 Insulation (51 mm extruded polystyrene caulked-in-place) which also formed an airtight air barrier and vapour barrier.



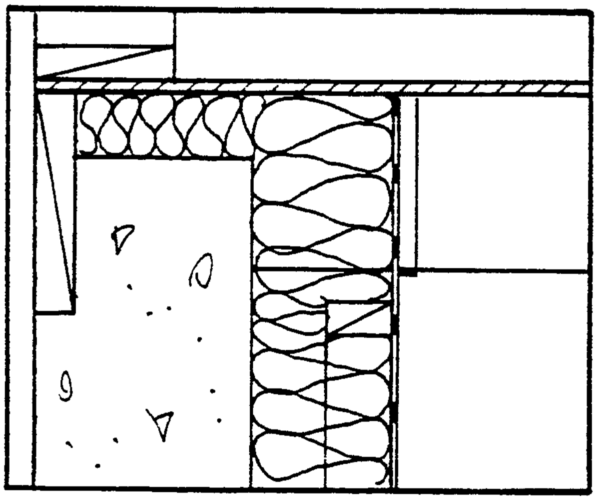
TYPICAL ATTIC TRUSS WMC INSTRUMENTATION
FIGURE 2



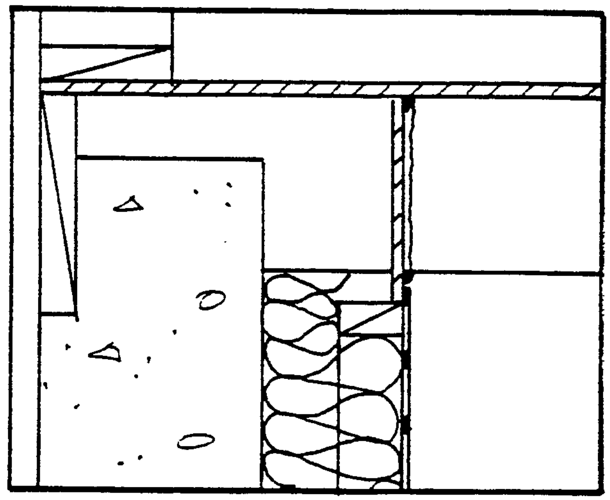
TYPE 1 - No Insulation
- No Air Barrier
- No Vapour Barrier



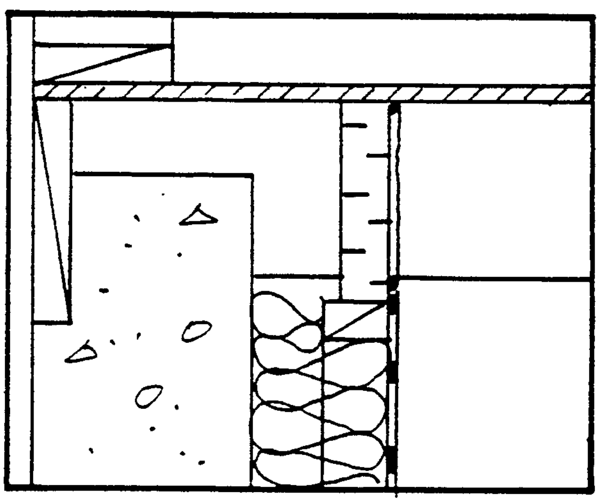
TYPE 2 - Glass Fibre Insulation
- No Air Barrier
- No Vapour Barrier



TYPE 3 - Glass Fibre Insulation
- No Air Barrier
- Polyethylene Vapour Barrier



TYPE 4 - No Insulation
- Plywood Air Barrier
- Plywood Vapour Barrier



TYPE 5 - Rigid Insulation
- Air Barrier
- Vapour Barrier

*Typical WMC Probe and Thermocouple Locations Shown for Type 1.

TYPICAL FLOOR JOIST
WMC INSTRUMENTATION

FIGURE 3

3.3 ANALYSIS

The monthly WMC data was recorded and entered into a custom-built, random access electronic data base in which the raw meter readings were edited and corrected for temperature and wood species using the equation suggested by Garrahan et al (1990):

$$M_c = (S - 0.0081T)M + (0.57 - 0.043T) \qquad (1)$$

where:
M_c = corrected moisture content (%)
S = species correction constant
T = wood temperature (°C)
M = uncorrected meter reading (%).

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

1. Mean WMC: Defined as the arithmetic mean WMC over the monitoring period, this parameter described the overall long-term moisture content of the wood and its susceptibility to decay.

2. Measurements Exceeding 19%: The number and percentage of WMC measurements which 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 was ignored.

3. Stability Below 19%: Since 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 below 19% if a) two consecutive monthly measurements above 19% were observed 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 was ignored.

The use of 19% as an indicator of potential moisture problems is a fairly conservative definition which may over-estimate the actual threat due to wood decay. It was chosen to provide a safety factor given that measurements made at a particular location in the envelope will not necessarily reflect those which occur at other spots.

3.4 INITIAL WOOD MOISTURE CONTENT

Samples of wood used in Houses #11 to #20 were collected on site at the time of construction to determine the initial moisture content of the framing materials. The moisture content was determined in accordance with ASTM D 2016 "Moisture Content of Wood" (1974). As shown in Table 5, levels were typically at, or slightly below, 19%, indicating that dry wood was used. Based on other observations and general knowledge of the quality of wood supplied in the Winnipeg area, these samples were considered representative of the wood used in the project houses.

3.5 RESULTS

Appendix A contains graphical summaries of the WMC measurements recorded at each of the 516 sampling locations. Table 6 summarizes this data for each sampling location including its performance relative to the three evaluation parameters discussed above. It also contains temperature, relative humidity, air change rate and mechanical pressurization data for the houses. The mean WMC levels recorded over the monitoring period are also displayed in Figs. 4 to 21 for each location.

TABLE 5

INITIAL WMC LEVELS

DATE	TYPE OF BOARD	MEAN BOARD WMC (%)	MEAN OF ALL SAMPLES (%)
December 19/85	38x89 (2x4) 38x89 (2x4)	14.9 14.9	14.9
January 28/86	38x140 (2x6) 38x140 (2x6)	18.6 18.8	18.7
February 20/86	38x140 (2x6) 38x140 (2x6) 38x140 (2x6) 38x140 (2x6) 38x140 (2x6) 38x140 (2x6) 38x140 (2x6)	19.1 17.0 20.1 20.9 18.0 19.8 18.0	19.0
March 18/86	38x64 (2x3) 38x64 (2x3)	18.1 18.8	18.5

TABLE 6

WOOD MOISTURE CONTENT

	PROBE*	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #1	NPTS	NO	12.4	0	YES
Average Interior Temperature 22 C	NPTC	NO	12.7	0	YES
Average Relative Humidity 39%	NPBS	NO	12.6	0	YES
Average Total Air Change Rate 0.40 ac/hr	NPBC	NO	12.6	0	YES
Average Mechanical Pressurization 0.4 Pa	NSCS	NO	12.1	0	YES
	NSCC	NO	12.1	0	YES
MEAN WMC	NSWS	NO	8.8	0	YES
Walls 10.4%	NSWC	NO	8.7	0	YES
Attic 7.9%	SPTS	NO	9.8	0	YES
	SPTC	NO	9.7	0	YES
	SPBS	NO	10.2	0	YES
	SPBC	NO	10.9	0	YES
	SSCS	NO	9.0	0	YES
	SSCC	NO	9.0	0	YES
	SSWS	NO	7.9	0	YES
	SSWC	NO	7.6	0	YES
	ABS	NO	7.9	0	YES
	ABC	NO	7.8	0	YES

HOUSE #2	NPTS	NO	12.4	0	YES
Average Interior Temperature 21 C	NPTC	NO	12.7	0	YES
Average Relative Humidity 46%	NPBS	NO	11.9	0	YES
Average Total Air Change Rate 0.28 ac/hr	NPBC	NO	12.5	0	YES
Average Mechanical Pressurization 0.2 Pa	NSCS	NO	12.0	0	YES
	NSCC	NO	11.5	0	YES
MEAN WMC	NSWS	NO	9.9	0	YES
Walls 11.2%	NSWC	NO	9.9	0	YES
Attic 8.7%	WPTS	NO	11.1	0	YES
	WPTC	NO	10.4	0	YES
	WPBS	NO	11.7	0	YES
	WPBC	NO	11.8	0	YES
	WSCS	NO	11.2	0	YES
	WSCC	NO	11.3	0	YES
	WSWS	NO	9.4	0	YES
	WSWC	NO	9.1	0	YES
	ABS	NO	9.0	0	YES
	ABC	NO	8.4	0	YES

* See notes at end of Table for probe nomenclature.

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #3	NPTS	NO	11.5	0	YES
Average Interior Temperature 19 C	NPTC	NO	10.9	0	YES
Average Relative Humidity 30%	NPBS	NO	11.3	0	YES
Average Total Air Change Rate 0.38 ac/hr	NPBC	NO	12.5	0	YES
Average Mechanical Pressurization 0.5 Pa	NSCS	NO	11.8	0	YES
	NSCC	NO	11.7	0	YES
MEAN WMC	NSWS	NO	9.7	0	YES
Walls 10.9%	NSWC	NO	10.1	0	YES
Attic 8.7%	WPTS	NO	12.4	0	YES
	WPTC	NO	11.5	0	YES
	WPBS	NO	10.8	0	YES
	WPBC	NO	11.2	0	YES
	WSCS	NO	10.7	0	YES
	WSCC	NO	10.8	0	YES
	WSWS	NO	8.8	0	YES
	WSWC	NO	8.9	0	YES
	ABS	NO	8.8	0	YES
	ABC	NO	8.6	0	YES
HOUSE #4	NPTS	NO	10.3	0	YES
Average Interior Temperature 19 C	NPTC	NO	11.3	0	YES
Average Relative Humidity 53%	NPBS	NO	16.2	7	YES
Average Total Air Change Rate 0.44 ac/hr	NPBC	NO	17.0	7	YES
Average Mechanical Pressurization -0.3 Pa	NSCS	NO	12.3	0	YES
	NSCC	NO	12.8	0	YES
MEAN WMC	NSWS	NO	9.7	0	YES
Walls 11.2%	NSWC	NO	10.1	0	YES
Attic 9.1%	EPTS	NO	9.7	0	YES
	EPTC	NO	9.5	0	YES
	EPBS	NO	11.6	4	YES
	EPBC	NO	11.8	4	YES
	ESCS	NO	9.7	0	YES
	ESCC	NO	9.8	0	YES
	ESWS	NO	8.8	0	YES
	ESWC	NO	8.5	0	YES
	ABS	NO	9.3	0	YES
	ABC	NO	8.8	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #5	NPTS	NO	10.0	0	YES
Average Interior Temperature 21 C	NPTC	NO	10.6	0	YES
Average Relative Humidity 27%	NPBS	NO	10.1	7	YES
Average Total Air Change Rate 0.63 ac/hr	NPBC	NO	14.5	0	YES
Average Mechanical Pressurization −3.5 Pa	NSCS	NO	10.2	0	YES
------------------------------------	NSCC	NO	10.2	0	YES
MEAN WMC	NSWS	NO	8.6	0	YES
Walls 10.5%	NSWC	NO	16.2	24	NO
Attic 8.3%	NSCS	NO	9.4	0	YES
	NSCC	NO	9.4	0	YES
	NSWS	NO	13.0	4	YES
	NSWC	NO	8.5	0	YES
	WPTS	NO	9.5	0	YES
	WPTC	NO	10.2	0	YES
	WPBS	NO	10.2	0	YES
	WPBC	NO	11.0	0	YES
	WSCS	NO	10.7	0	YES
	WSCC	NO	10.8	0	YES
	WSWS	NO	8.8	0	YES
	WSWC	NO	8.5	0	YES
	ABS	NO	8.1	0	YES
	ABC	NO	8.5	0	YES

HOUSE #6	NPTS	NO	14.0	0	YES
Average Interior Temperature 20 C	NPTC	NO	12.7	0	YES
Average Relative Humidity 34%	NPBS	NO	15.6	0	YES
Average Total Air Change Rate 0.37 ac/hr	NPBC	NO	13.9	0	YES
Average Mechanical Pressurization −1.6 Pa	NSCS	NO	10.8	0	YES
------------------------------------	NSCC	NO	13.2	0	YES
MEAN WMC	NSWS	NO	9.4	0	YES
Walls 11.5%	NSWC	NO	10.1	0	YES
Attic 9.1%	WPTS	NO	13.6	11	NO
	WPTC	NO	8.5	0	YES
	WPBS	NO	12.7	0	YES
	WPBC	NO	11.8	0	YES
	WSCS	NO	12.2	0	YES
	WSCC	NO	12.3	4	YES
	WSWS	NO	8.8	0	YES
	WSWC	NO	8.9	0	YES
	ESCS	NO	9.3	0	YES
	ESCC	NO	9.3	0	YES
	ABS	NO	9.4	0	YES
	ABC	NO	8.8	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #7	NPTS	NO	16.2	20	NO
Average Interior Temperature 22 C	NPTC	NO	15.2	0	YES
Average Relative Humidity 31%	NPBS	NO	15.9	7	YES
Average Total Air Change Rate 0.14 ac/hr	NPBC	NO	16.1	7	YES
Average Mechanical Pressurization 0.0 Pa	NSCS	NO	19.6	70	NO
	NSCC	NO	17.1	10	YES
MEAN WMC	NSWS	NO	9.0	0	YES
Walls 12.8%	NSWC	NO	9.3	0	YES
Attic 8.3%	WPTS	NO	11.3	0	YES
	WPTC	NO	11.1	0	YES
	WPBS	NO	9.7	0	YES
	WPBC	NO	15.8	7	YES
	WSCS	NO	12.2	0	YES
	WSCC	NO	12.1	0	YES
	WSWS	NO	8.6	0	YES
	WSWC	NO	8.8	0	YES
	ABS	NO	8.2	0	YES
	ABC	NO	8.3	0	YES

HOUSE #8	NPTS	NO	16.6	24	NO
Average Interior Temperature 21 C	NPTC	NO	16.3	3	YES
Average Relative Humidity 36%	NPBS	NO	15.6	3	YES
Average Total Air Change Rate 0.11 ac/hr	NPBC	NO	16.9	17	NO
Average Mechanical Pressurization 0.0 Pa	NSCS	NO	17.9	31	NO
	NSCC	NO	16.6	14	NO
MEAN WMC	NSWS	NO	9.0	0	YES
Walls 12.0%	NSWC	NO	9.6	0	YES
Attic 9.1%	SPTS	NO	9.3	0	YES
	SPTC	NO	10.8	0	YES
	SPBS	NO	9.2	0	YES
	SPBC	NO	9.3	0	YES
	SSCS	NO	9.5	0	YES
	SSCC	NO	9.7	0	YES
	SSWS	NO	7.6	0	YES
	SSWC	NO	7.8	0	YES
	ABS	NO	9.2	0	YES
	ABC	NO	8.9	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #9	NPTS	NO	11.8	0	YES
Average Interior Temperature 20 C	NPTC	NO	12.7	0	YES
Average Relative Humidity __%	NPBS	NO	13.4	3	YES
Average Total Air Change Rate 0.11 ac/hr	NPBC	NO	14.2	0	YES
Average Mechanical Pressurization ___ Pa	NSCS	NO	11.4	0	YES
	NSCC	NO	11.7	0	YES
MEAN WMC	NSWS	NO	8.8	0	YES
Walls 10.3%	NSWC	NO	10.3	3	YES
Attic 9.9%	SPTS	NO	9.7	0	YES
	SPTC	NO	9.0	0	YES
	SPBS	NO	9.2	0	YES
	SPBC	NO	9.8	0	YES
	SSCS	NO	8.8	0	YES
	SSCC	NO	8.7	0	YES
	SSWS	NO	7.9	0	YES
	SSWC	NO	8.0	0	YES
	ABS	NO	10.5	3	YES
	ABC	NO	9.2	3	YES
HOUSE #10	NPTS	NO	14.8	0	YES
Average Interior Temperature 23 C	NPTC	NO	14.2	0	YES
Average Relative Humidity __%	NPBS	NO	12.8	0	YES
Average Total Air Change Rate 0.10 ac/hr	NPBC	NO	13.3	0	YES
Average Mechanical Pressurization ___ Pa	NSCS	NO	12.5	0	YES
	NSCC	NO	12.6	0	YES
MEAN WMC	NSWS	NO	8.4	0	YES
Walls 11.3%	NSWC	NO	9.0	0	YES
Attic 9.0%	WPTS	NO	9.7	0	YES
	WPTC	NO	10.0	0	YES
	WPBS	NO	12.7	0	YES
	WPBC	NO	13.2	0	YES
	WSCS	NO	10.2	0	YES
	WSCC	NO	10.0	0	YES
	WSWS	NO	8.3	0	YES
	WSWC	NO	8.3	0	YES
	ABS	NO	9.5	0	YES
	ABC	NO	8.4	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #11	NPTS	NO	10.9	0	YES
Average Interior Temperature 21 C	NPTC	NO	11.1	0	YES
Average Relative Humidity 29%	NPBS	NO	12.2	0	YES
Average Total Air Change Rate 0.36 ac/hr	NPBC	NO	12.2	0	YES
Average Mechanical Pressurization −15.1 Pa	NSCS	NO	10.6	0	YES
	NSCC	NO	10.4	0	YES
MEAN WMC	NSWS	NO	8.7	0	YES
Walls 10.2%	NSWC	NO	8.7	0	YES
Attic 8.9%	NSCS	YES	11.3	0	YES
	NSCC	YES	11.1	0	YES
	WPTS	NO	10.2	0	YES
	WPTC	NO	10.3	0	YES
	WPBS	NO	11.9	0	YES
	WPBC	NO	11.2	0	YES
	WSCS	NO	9.8	0	YES
	WSCC	NO	9.9	0	YES
	WSWS	NO	8.6	0	YES
	WSWC	NO	8.7	0	YES
	EPTS	NO	9.4	0	YES
	EPTC	NO	9.4	0	YES
	EPBS	NO	10.5	0	YES
	EPBC	NO	10.6	0	YES
	ESCS	NO	9.9	0	YES
	ESCC	NO	10.1	0	YES
	ESWS	NO	8.5	0	YES
	ESWC	NO	8.5	0	YES
	ESCS	YES	11.9	0	YES
	ESCC	YES	12.1	0	YES
	ESCS	YES	10.6	0	YES
	ESCC	YES	10.4	0	YES
	ESCS	YES	9.2	0	YES
	ESCC	YES	9.4	0	YES
	ESCS	YES	9.9	0	YES
	ESCC	YES	9.7	0	YES
	ABS	NO	7.9	0	YES
	ABC	NO	7.9	0	YES
	ATS	NO	9.9	0	YES
	ATC	NO	9.7	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #12	NPTS	NO	9.2	0	YES
Average Interior Temperature 23 C	NPTC	NO	9.2	0	YES
Average Relative Humidity 24%	NPBS	NO	10.8	0	YES
Average Total Air Change Rate 0.42 ac/hr	NPBC	NO	10.8	0	YES
Average Mechanical Pressurization -15.8 Pa	NSCS	NO	10.2	0	YES
------------------------------------	NSCC	NO	9.6	0	YES
MEAN WMC	NSWS	NO	7.8	0	YES
Walls 9.4%	NSWC	NO	7.9	0	YES
Attic 8.9%	NSCS	YES	10.1	0	YES
	NSCC	YES	9.5	0	YES
	EPTS	NO	9.2	0	YES
	EPTC	NO	9.4	0	YES
	EPBS	NO	11.1	0	YES
	EPBC	NO	11.5	0	YES
	ESCS	NO	9.1	0	YES
	ESCC	NO	8.9	0	YES
	ESWS	NO	8.3	0	YES
	ESWC	NO	8.1	0	YES
	ESCS	YES	8.8	0	YES
	ESCC	YES	8.6	0	YES
	ESCS	YES	8.7	0	YES
	ESCC	YES	8.8	0	YES
	ESCS	YES	8.7	0	YES
	ESCC	YES	8.3	0	YES
	ESCS	YES	9.0	0	YES
	ESCC	YES	9.1	0	YES
	WPTS	NO	9.8	0	YES
	WPTC	NO	9.7	0	YES
	WPBS	NO	11.3	0	YES
	WPBC	NO	11.5	4	YES
	WSCS	NO	9.6	0	YES
	WSCC	NO	9.1	0	YES
	WSWS	NO	8.7	0	YES
	WSWC	NO	9.1	0	YES
	ABS	NO	7.7	0	YES
	ABC	NO	7.7	0	YES
	ATS	NO	10.4	0	YES
	ATC	NO	9.9	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #15	NPTS	NO	9.2	0	YES
Average Interior Temperature 24 C	NPTC	NO	9.4	0	YES
Average Relative Humidity 39%	NPBS	NO	10.3	0	YES
Average Total Air Change Rate ____ ac/hr	NPBC	NO	10.1	0	YES
Average Mechanical Pressurization _____ Pa	NSCS	NO	8.9	0	YES
	NSCC	NO	9.0	0	YES
MEAN WMC	NSWS	NO	8.2	0	YES
Walls 9.0%	NSWC	NO	8.3	0	YES
Attic 8.2%	ESCS	NO	8.6	0	YES
	ESCC	NO	8.7	0	YES
	ESWS	NO	9.8	0	YES
	ESWC	NO	9.9	0	YES
	EPTS	NO	9.1	0	YES
	EPTC	NO	8.3	0	YES
	EPBS	NO	8.0	0	YES
	EPBC	NO	8.2	0	YES
	NSCS	YES	10.8	0	YES
	NSCC	YES	10.5	0	YES
	ESCS	YES	8.5	0	YES
	ESCC	YES	8.7	0	YES
	SPTS	NO	9.5	0	YES
	SPTC	NO	9.8	0	YES
	SPBS	NO	8.5	0	YES
	SPBC	NO	8.5	0	YES
	SSCS	NO	8.3	0	YES
	SSCC	NO	8.3	0	YES
	SSWS	NO	8.4	0	YES
	SSWC	NO	8.5	0	YES
	ABS	NO	7.7	0	YES
	ABC	NO	7.6	0	YES
	ATS	NO	8.8	0	YES
	ATC	NO	8.6	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #16	NPTS	NO	8.8	0	YES
Average Interior Temperature 21 C	NPTC	NO	9.2	0	YES
Average Relative Humidity 49%	NPBS	NO	10.1	0	YES
Average Total Air Change Rate ____ ac/hr	NPBC	NO	10.5	0	YES
Average Mechanical Pressurization _____ Pa	NSCS	NO	10.3	0	YES
	NSCC	NO	10.1	0	YES
MEAN WMC	NSWS	NO	8.7	0	YES
Walls 9.3%	NSWC	NO	8.7	0	YES
Attic 8.2%	NSCS	YES	11.8	0	YES
	NSCC	YES	11.5	0	YES
	ESCS	YES	10.8	0	YES
	ESCC	YES	11.2	0	YES
	SPTS	NO	8.6	0	YES
	SPTC	NO	8.7	0	YES
	SPBS	NO	9.1	0	YES
	SPBC	NO	8.7	0	YES
	SSCS	NO	9.1	0	YES
	SSCC	NO	9.7	0	YES
	SSWS	NO	8.1	0	YES
	SSWC	NO	8.2	0	YES
	EPTS	NO	8.7	0	YES
	EPTC	NO	8.9	0	YES
	EPBS	NO	8.2	0	YES
	EPBC	NO	8.3	0	YES
	ESCS	NO	9.1	0	YES
	ESCC	NO	9.7	0	YES
	ESWS	NO	8.1	0	YES
	ESWC	NO	8.2	0	YES
	ABS	NO	7.9	0	YES
	ABC	NO	7.9	0	YES
	ATS	NO	8.5	0	YES
	ATC	NO	8.5	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #18	EA1	NO	11.1	0	YES
Average Interior Temperature 21 C	EB1	NO	9.2	0	YES
Average Relative Humidity 41%	EC1	NO	10.6	0	YES
Average Total Air Change Rate 0.40 ac/hr	ED1	NO	8.9	0	YES
Average Mechanical Pressurization _____ Pa	WA1	NO	9.7	0	YES
	WB1	NO	9.7	0	YES
MEAN WMC	WC1	NO	9.6	0	YES
Floor Joists, Type 1 9.6%	WD1	NO	8.1	0	YES
Floor Joists, Type 2 10.7%	EA2	NO	11.5	0	YES
Floor Joists, Type 3 11.2%	EB2	NO	11.1	0	YES
Floor Joists, Type 4 10.0%	EC2	NO	11.6	0	YES
Floor Joists, Type 5 10.2%	ED2	NO	7.5	0	YES
	WA2	NO	13.6	0	YES
	WB2	NO	12.3	0	YES
	WC2	NO	9.3	0	YES
	WD2	NO	8.8	0	YES
	EA3	NO	12.4	0	YES
	EB3	NO	12.3	0	YES
	EC3	NO	12.5	0	YES
	ED3	NO	7.3	0	YES
	WA3	NO	12.0	0	YES
	WB3	NO	11.3	0	YES
	WC3	NO	13.4	0	YES
	WD3	NO	8.0	0	YES
	EA4	NO	7.6	0	YES
	EB4	NO	12.2	0	YES
	EC4	NO	12.0	0	YES
	ED4	NO	7.4	0	YES
	WA4	NO	8.2	0	YES
	WB4	NO	12.6	0	YES
	WC4	NO	11.8	0	YES
	WD4	NO	8.3	0	YES
	EA5	NO	10.7	0	YES
	EB5	NO	11.1	0	YES
	EC5	NO	11.4	0	YES
	ED5	NO	7.7	0	YES
	WA5	NO	11.4	0	YES
	WB5	NO	9.3	0	YES
	WC5	NO	12.6	0	YES
	WD5	NO	7.7	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #19	NPTS	NO	9.7	0	YES
Average Interior Temperature 21 C	NPTC	NO	10.2	0	YES
Average Relative Humidity 33%	NPBS	NO	12.9	0	YES
Average Total Air Change Rate 0.60 ac/hr	NPBC	NO	13.0	0	YES
Average Mechanical Pressurization -5.6 Pa	NSCS	NO	9.9	0	YES
------------------------------------	NSCC	NO	10.1	0	YES
MEAN WMC	NSWS	NO	8.8	0	YES
Walls 10.1%	NSWC	NO	8.8	0	YES
Attic 9.1%	NSCS	YES	9.1	0	YES
	NSCC	YES	9.0	0	YES
	EPTS	NO	10.0	0	YES
	EPTC	NO	10.3	0	YES
	EPBS	NO	12.4	0	YES
	EPBC	NO	11.2	0	YES
	ESCS	NO	9.8	0	YES
	ESCC	NO	10.1	0	YES
	ESWS	NO	9.0	0	YES
	ESWC	NO	9.2	0	YES
	ESCS	YES	8.6	0	YES
	ESCC	YES	8.7	0	YES
	ESCS	YES	8.1	0	YES
	ESCC	YES	8.3	0	YES
	ESCS	YES	9.6	0	YES
	ESCC	YES	10.1	0	YES
	WPTS	NO	10.5	0	YES
	WPTC	NO	10.4	0	YES
	WPBS	NO	12.9	0	YES
	WPBC	NO	12.7	0	YES
	WSCS	NO	9.7	0	YES
	WSCC	NO	10.4	0	YES
	WSWS	NO	9.1	0	YES
	WSWC	NO	9.2	0	YES
	ABS	NO	8.1	0	YES
	ABC	NO	8.3	0	YES
	ATS	NO	10.0	0	YES
	ATC	NO	9.8	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #20	NPTS	NO	8.9	0	YES
Average Interior Temperature 21 C	NPTC	NO	8.9	0	YES
Average Relative Humidity 47%	NPBS	NO	10.7	0	YES
Average Total Air Change Rate 0.49 ac/hr	NPBC	NO	10.7	0	YES
Average Mechanical Pressurization 0.4 Pa	NSCS	NO	10.6	0	YES
	NSCC	NO	10.8	0	YES
MEAN WMC	NSWS	NO	8.6	0	YES
Walls 9.7%	NSWC	NO	8.9	0	YES
Attic 8.8%	NSCS	YES	10.0	0	YES
Floor Joists, Type 1 8.4%	NSCC	YES	8.9	0	YES
Floor Joists, Type 2 9.1%	EPTS	NO	10.0	0	YES
Floor Joists, Type 3 9.4%	EPTC	NO	9.8	0	YES
Floor Joists, Type 4 8.9%	EPBS	NO	10.1	0	YES
Floor Joists, Type 5 11.6%	EPBC	NO	10.4	0	YES
	ESCS	NO	9.5	0	YES
	ESCC	NO	9.4	0	YES
	ESWS	NO	8.7	0	YES
	ESWC	NO	8.8	0	YES
	ESCS	YES	9.1	0	YES
	ESCC	YES	9.5	0	YES
	ESCS	YES	11.0	0	YES
	ESCC	YES	11.1	0	YES
	ESCS	YES	8.2	0	YES
	ESCC	YES	8.2	0	YES
	ESCS	YES	9.2	0	YES
	ESCC	YES	9.2	0	YES
	WPTS	NO	9.9	0	YES
	WPTC	NO	9.8	0	YES
	WPBS	NO	9.7	0	YES
	WPBC	NO	10.1	0	YES
	WSCS	NO	11.1	0	YES
	WSCC	NO	11.3	0	YES
	WSWS	NO	9.6	0	YES
	WSWC	NO	9.6	0	YES
	ABS	NO	8.0	0	YES
	ABC	NO	8.0	0	YES
	ATS	NO	9.8	0	YES
	ATC	NO	9.4	0	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #20	EA1	NO	8.2	0	YES
	EB1	NO	8.5	0	YES
	EC1	NO	9.4	0	YES
	ED1	NO	8.2	0	YES
	WA1	NO	8.4	0	YES
	WB1	NO	8.0	0	YES
	WC1	NO	8.9	0	YES
	WD1	NO	7.6	0	YES
	EA2	NO	9.3	0	YES
	EB2	NO	9.7	0	YES
	EC2	NO	10.1	0	YES
	ED2	NO	8.1	0	YES
	WA2	NO	8.5	0	YES
	WB2	NO	9.1	3	YES
	WC2	NO	10.0	3	YES
	WD2	NO	8.3	3	YES
	EA3	NO	9.8	0	YES
	EB3	NO	9.8	0	YES
	EC3	NO	9.9	0	YES
	ED3	NO	8.1	0	YES
	WA3	NO	10.4	3	YES
	WB3	NO	9.7	3	YES
	WC3	NO	10.0	0	YES
	WD3	NO	7.5	0	YES
	EA4	NO	9.9	0	YES
	EB4	NO	9.0	0	YES
	EC4	NO	10.3	0	YES
	ED4	NO	8.2	0	YES
	WA4	NO	7.2	0	YES
	WB4	NO	8.2	0	YES
	WC4	NO	10.3	0	YES
	WD4	NO	8.2	3	YES
	EA5	NO	8.1	0	YES
	EB5	NO	9.2	0	YES
	EC5	NO	9.9	0	YES
	ED5	NO	8.0	0	YES
	WA5	NO	9.0	3	YES
	WB5	NO	9.6	0	YES
	WC5	NO	10.7	3	YES
	WD5	NO	28.0	78	YES

TABLE 6 (con't)

WOOD MOISTURE CONTENT

	PROBE	PROXIMITY TO ANOMALY?	MEAN WMC (%)	PERCENTAGE OF READINGS ABOVE 19%	WMC STABLE BELOW 19%? (YES/NO)
HOUSE #23	NPTS	NO	12.6	0	YES
Average Interior Temperature 21 C	NPTC	NO	12.0	0	YES
Average Relative Humidity __%	NPBS	NO	11.1	0	YES
Average Total Air Change Rate 0.31 ac/hr	NPBC	NO	11.9	0	YES
Average Mechanical Pressurization -0.2 Pa	NSCS	NO	11.5	0	YES
------------------------------------	NSCC	NO	11.8	0	YES
MEAN WMC	NSWS	NO	10.2	0	YES
Walls 11.7%	NSWC	NO	10.3	0	YES
Strapping 8.8%	EPTS	NO	11.1	0	YES
	EPTC	NO	10.7	0	YES
	EPBS	NO	10.7	0	YES
	EPBC	NO	10.8	0	YES
	ESCS	NO	10.2	0	YES
	ESCC	NO	10.3	0	YES
	ESWS	NO	9.6	0	YES
	ESWC	NO	9.7	0	YES
	WSCS	NO	10.5	0	YES
	WSCC	NO	13.7	0	YES
	WSWS	NO	9.5	0	YES
	WSWC	NO	24.8	43	NO
	NTS	NO	8.7	0	YES
	NTC	NO	9.1	0	YES
	NMS	NO	8.8	0	YES
	NMC	NO	8.9	0	YES
	NBS	NO	9.1	0	YES
	NBC	NO	9.2	0	YES
	ETS	NO	8.8	0	YES
	ETC	NO	8.3	0	YES
	EMS	NO	8.0	0	YES
	EMC	NO	7.9	0	YES
	EBS	NO	8.9	0	YES
	EBC	NO	8.7	0	YES
	WTS	NO	8.8	0	YES
	WTC	NO	8.8	0	YES
	WMS	NO	9.1	0	YES
	WMC	NO	9.2	0	YES

TABLE 6 (con't)

NOTES:

1. The data for the Percentage of WMC Readings Exceeding 19% and the data indicating whether the WMC was Stable Below 19% both ignore the initial dry-out period of 1 to 2 months.

2. WMC PROBE NOMENCLATURE:

4 characters; e.g.: N--Wall direction (North, East, South, West)
P--Plate (top or bottom) or Stud
T--Top or Bottom of cavity or Warm or Cold side of stud
S--Shell or Core of member

3 characters beginning with "A"; e.g.:
A--Attic
B--Bottom chord or Top chord
S--Shell or Core of member

3 characters beginning with "E" or "W", Houses #18 and #20 only; e.g.:
E--Wall direction (East or West)
A--Position on floor joist (A,B,C, or D)
1--Floor joist header insulation/sealing method (1,2,3,4,5)

3 characters beginning with "E" or "W", House #23 only, denotes horizontal strapping; e.g.: N--Wall direction (North, East or West)
T--Height of strapping (Top, Mid-Height or Bottom of wall)
S--Shell or Core of member

FIGURE 4

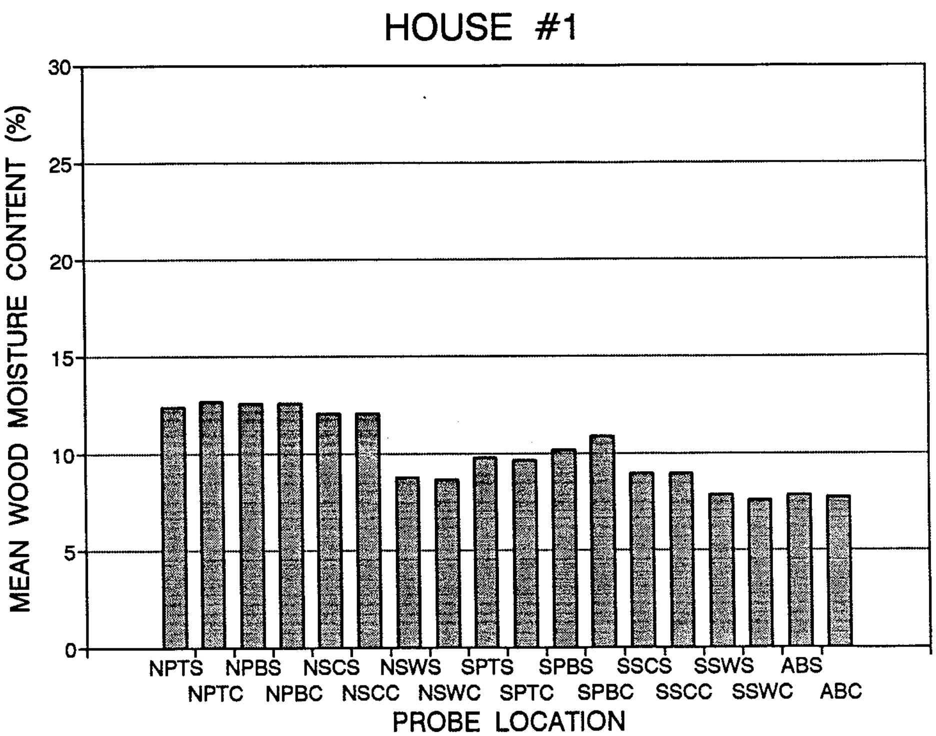


FIGURE 5

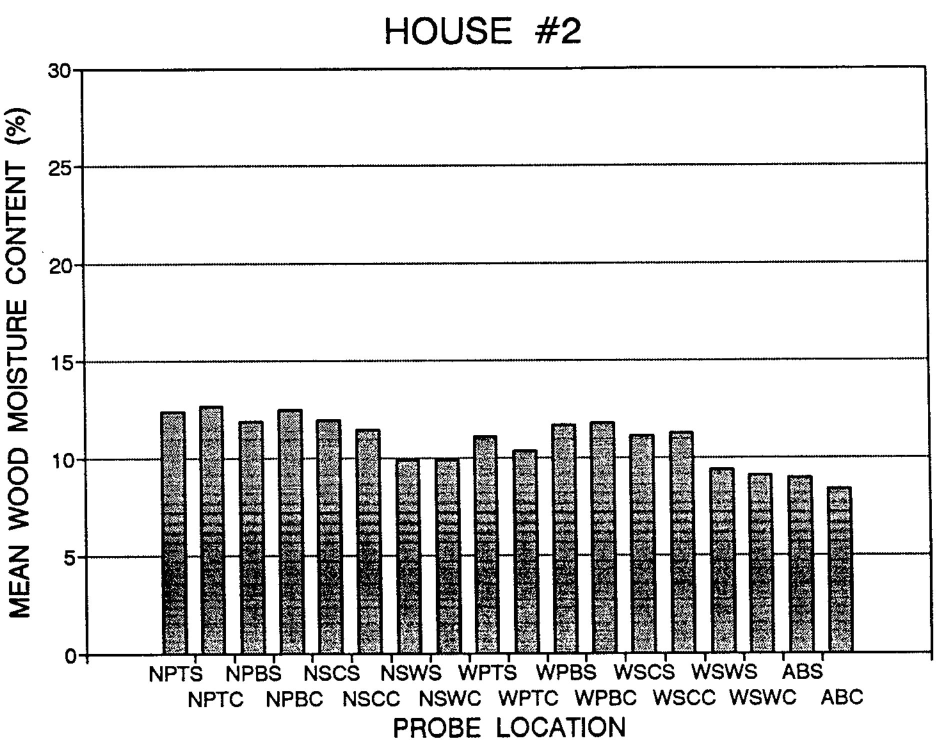


FIGURE 6

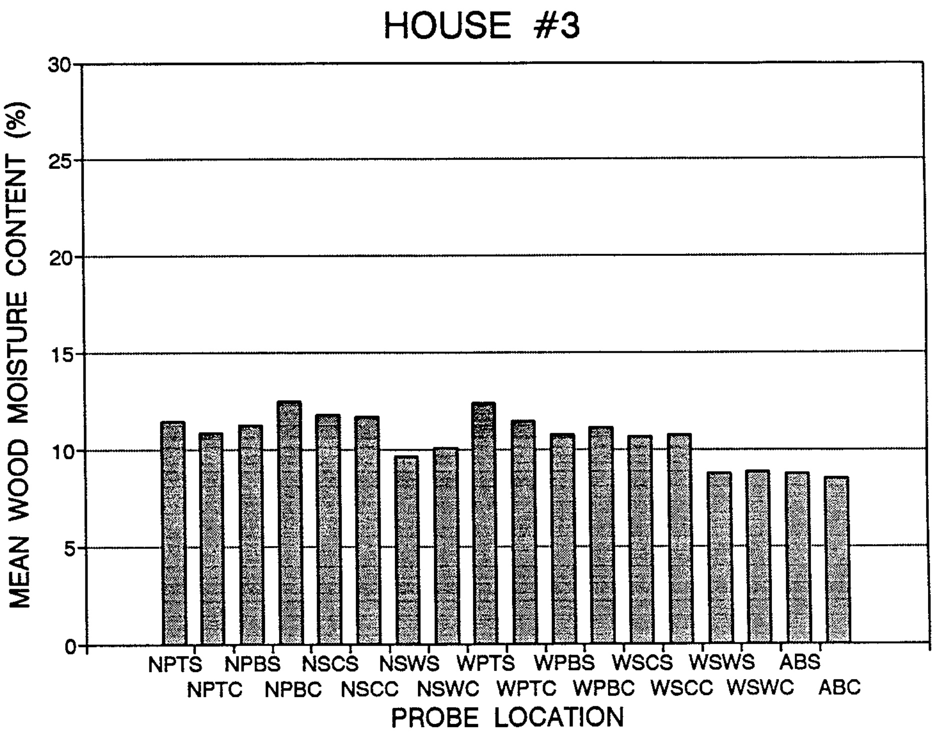


FIGURE 7

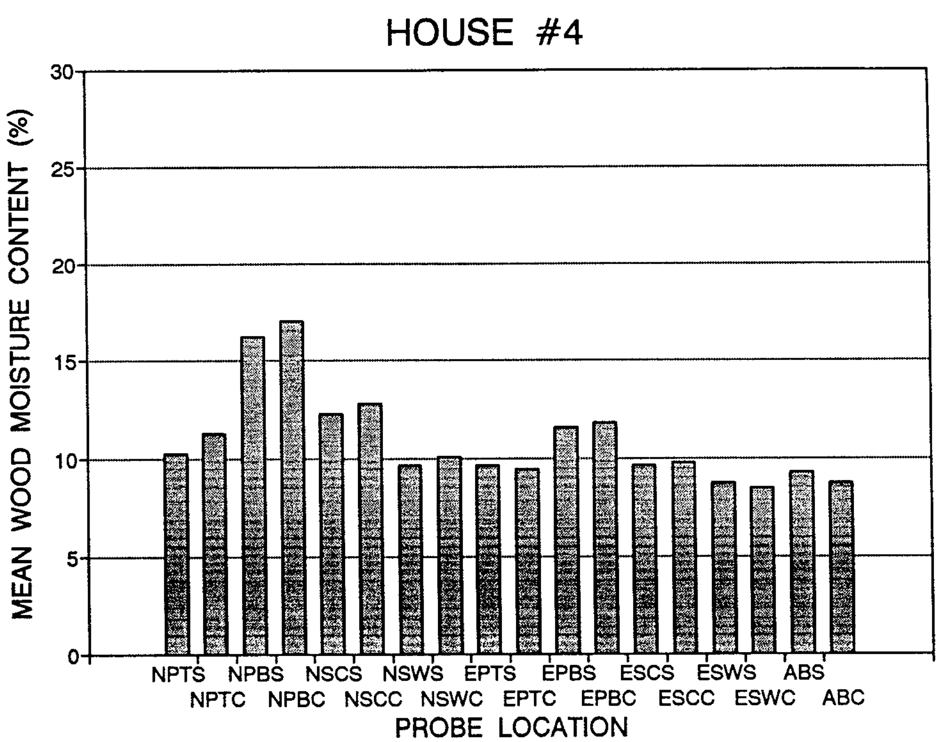


FIGURE 8

HOUSE #5

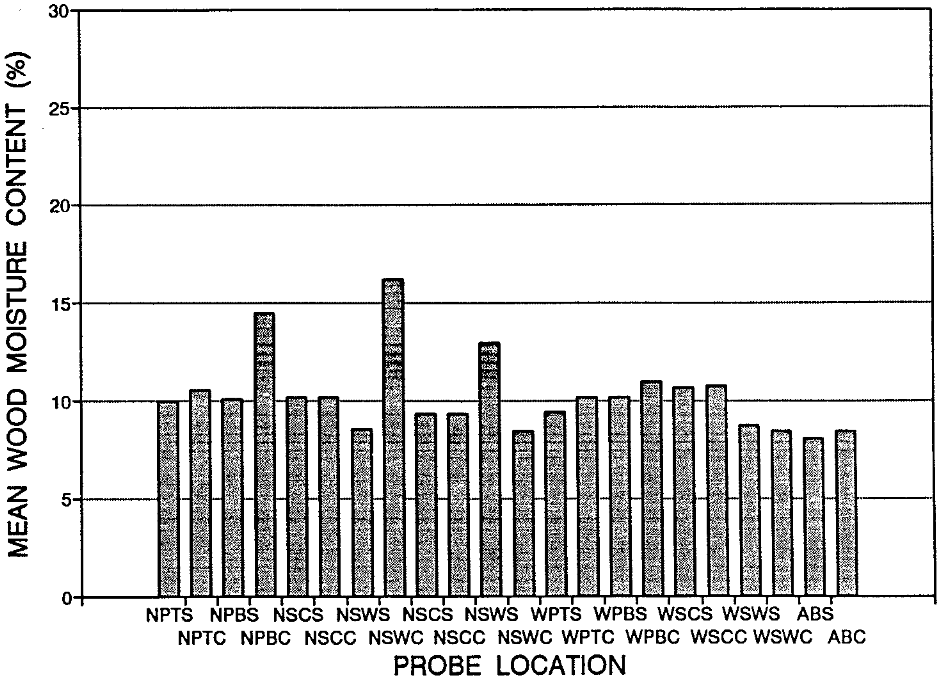


FIGURE 9

HOUSE #6

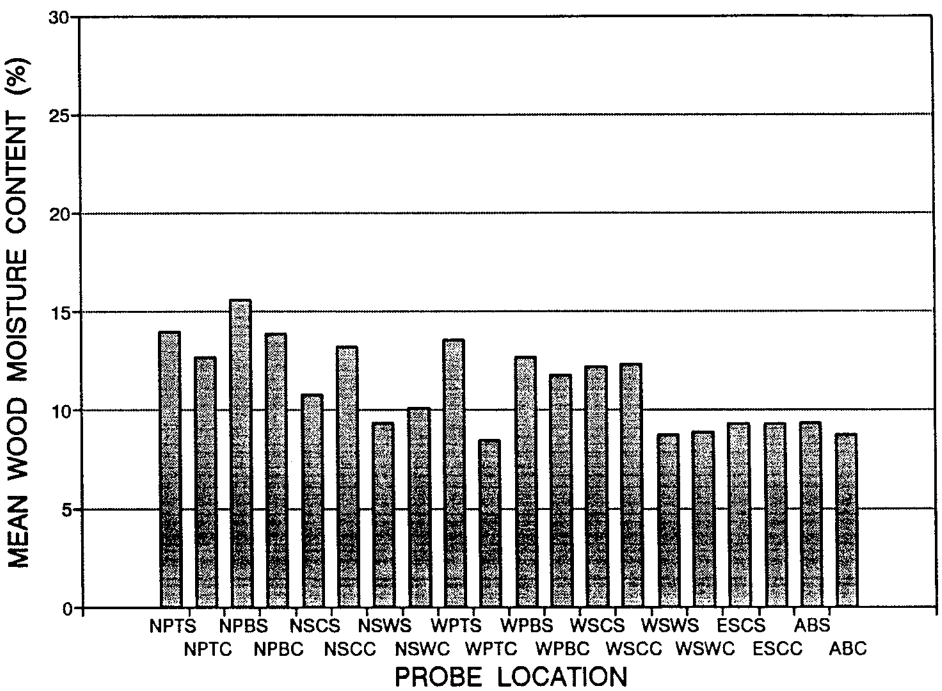


FIGURE 10

HOUSE #7

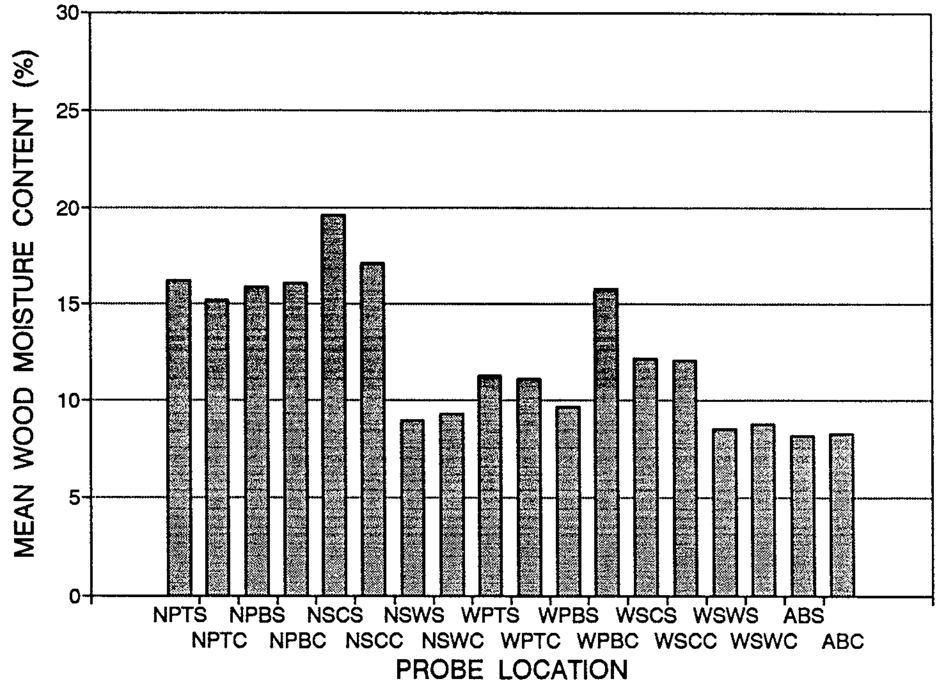


FIGURE 11

HOUSE #8

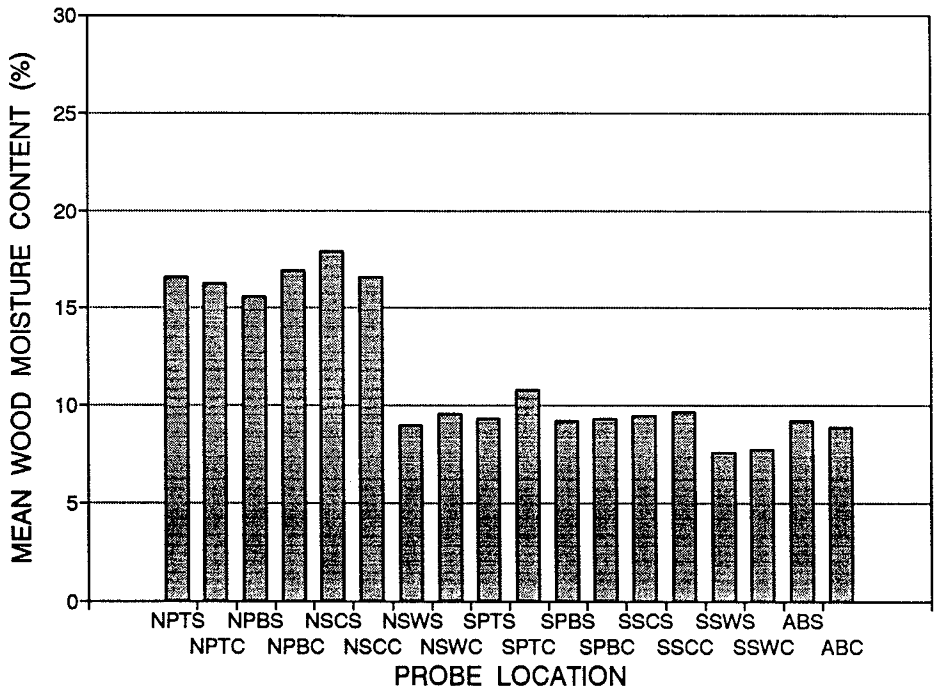


FIGURE 12

HOUSE #9

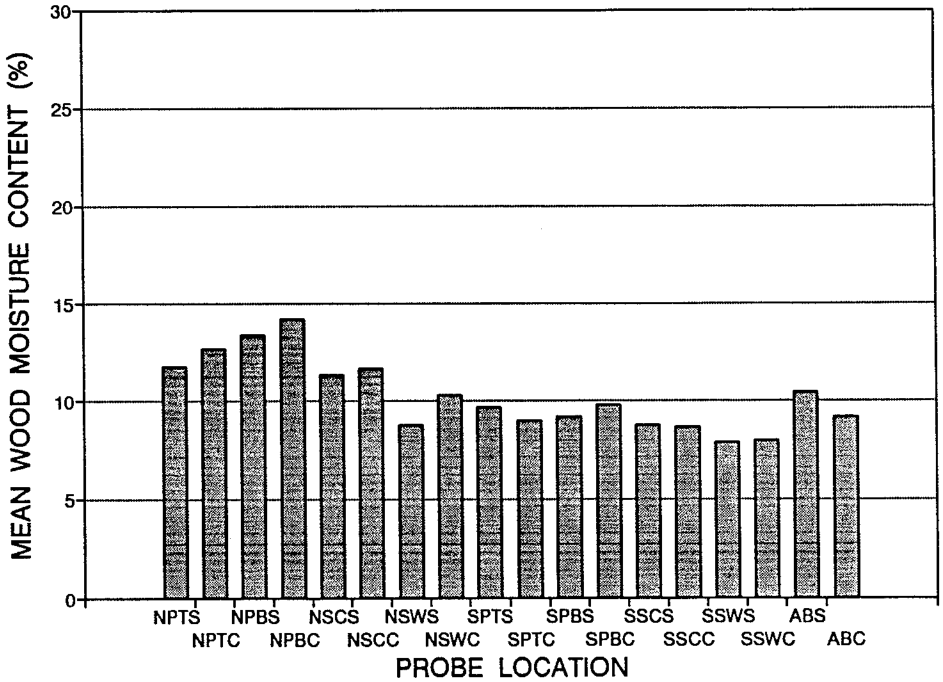


FIGURE 13

HOUSE #10

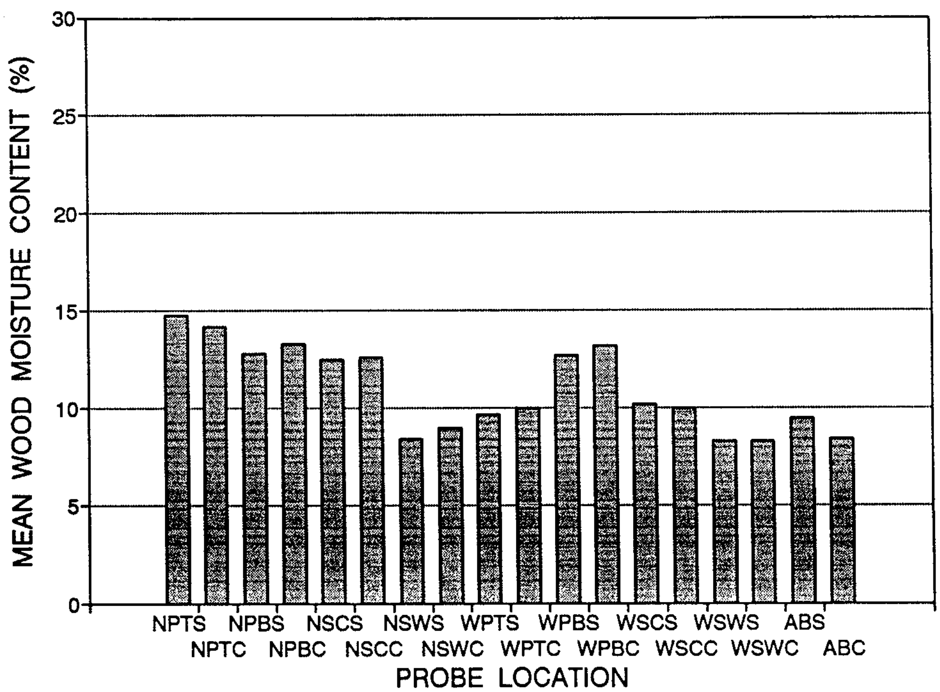


FIGURE 14(a)

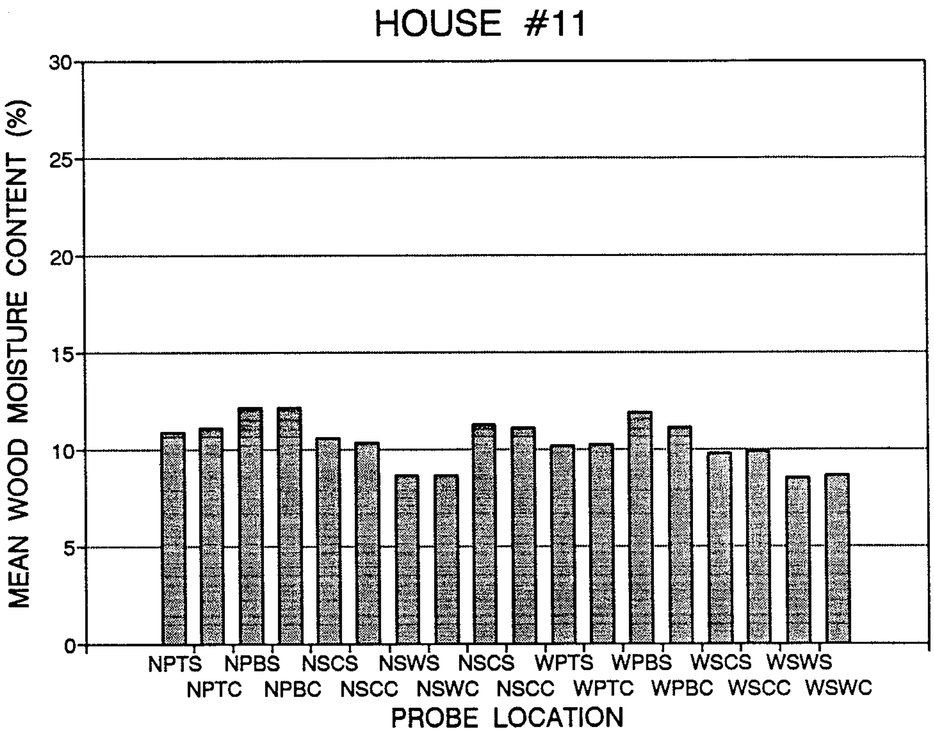


FIGURE 14(b)

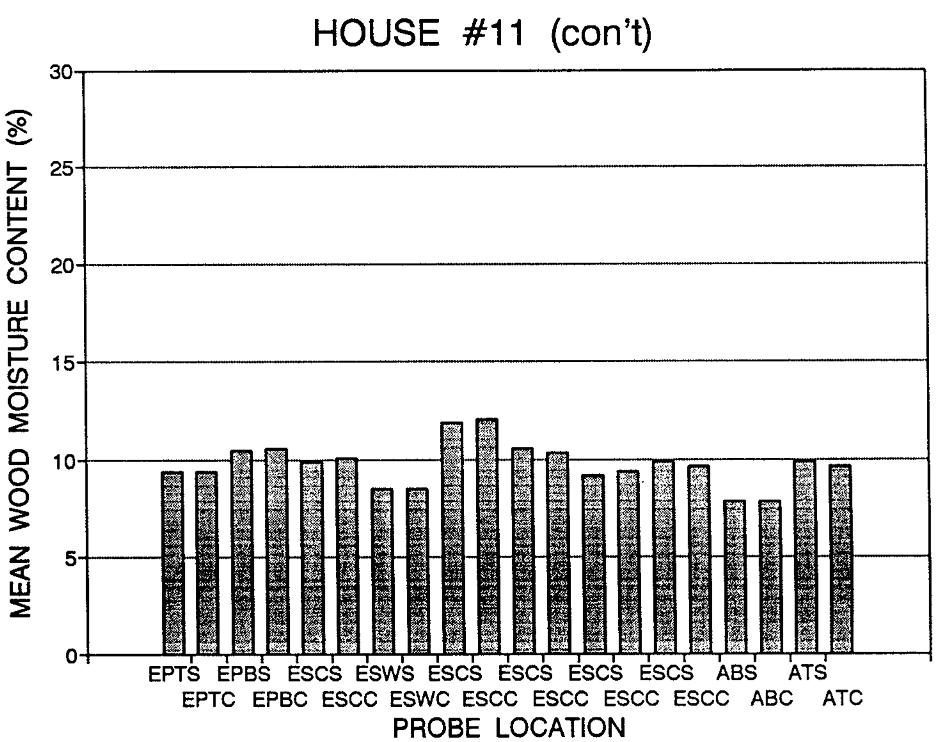


FIGURE 15(a)

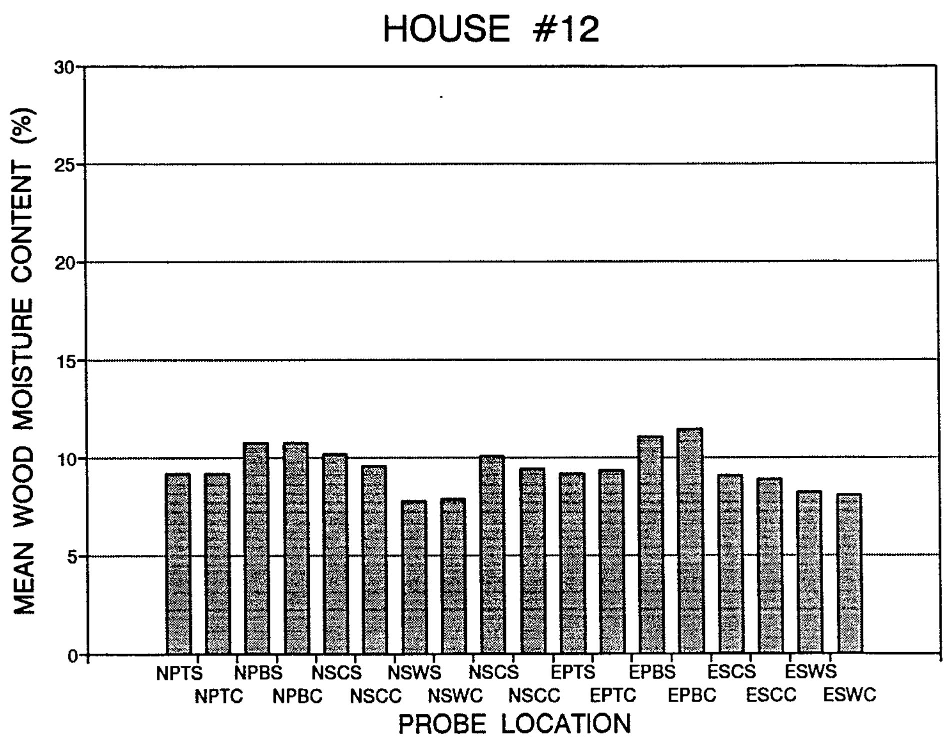


FIGURE 15(b)

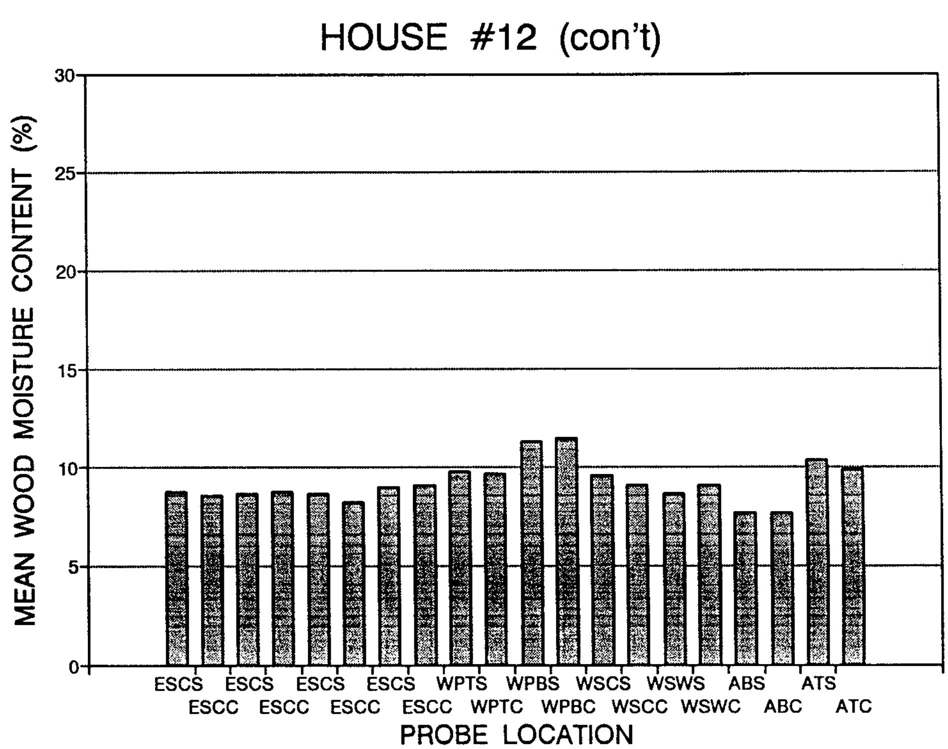


FIGURE 16(a)

HOUSE #15

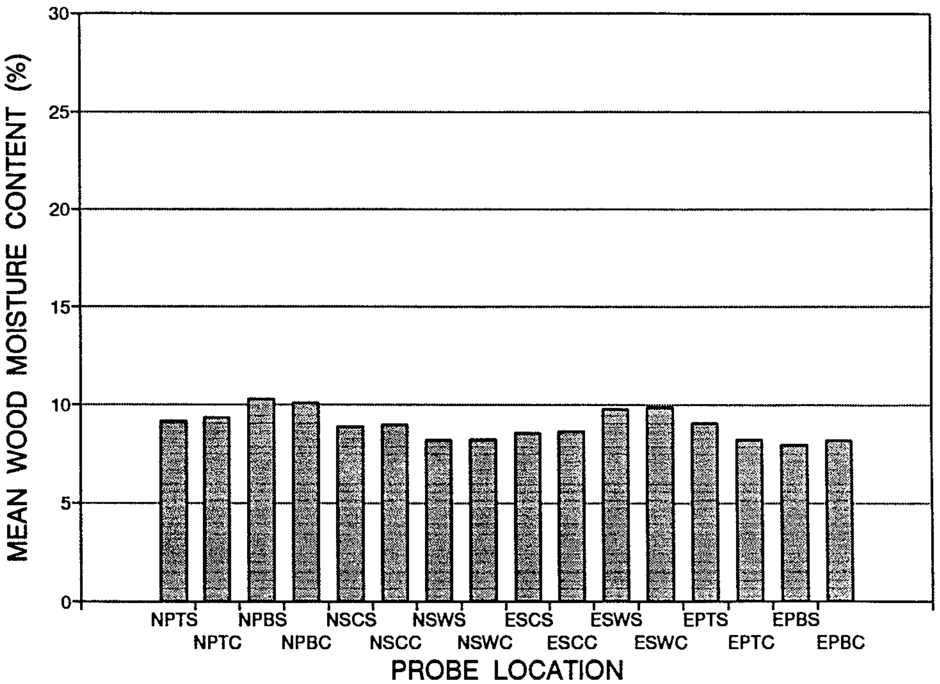


FIGURE 16(b)

HOUSE #15 (con't)

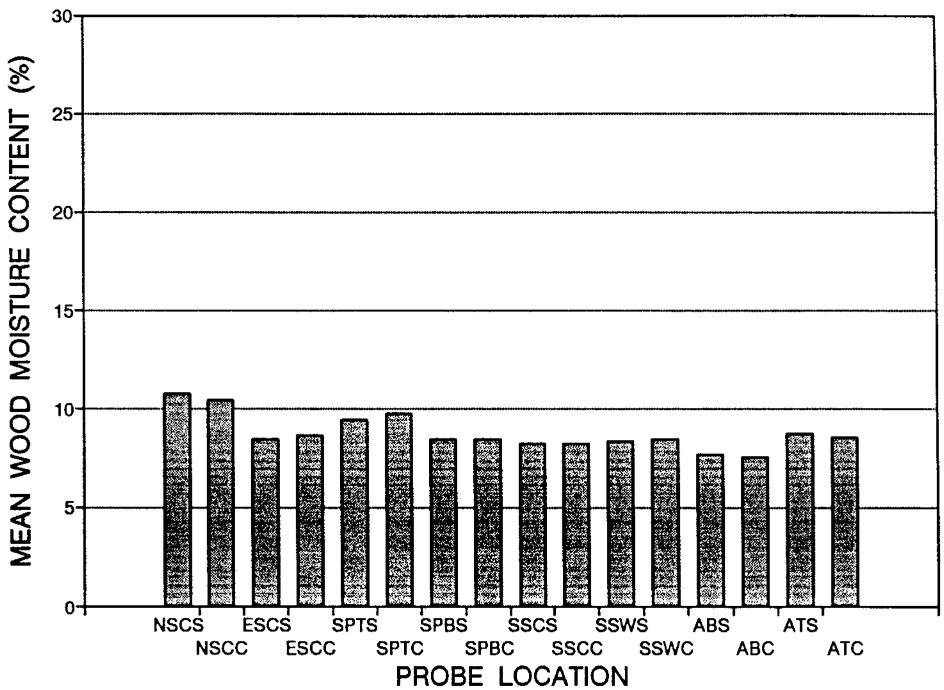


FIGURE 17(a)

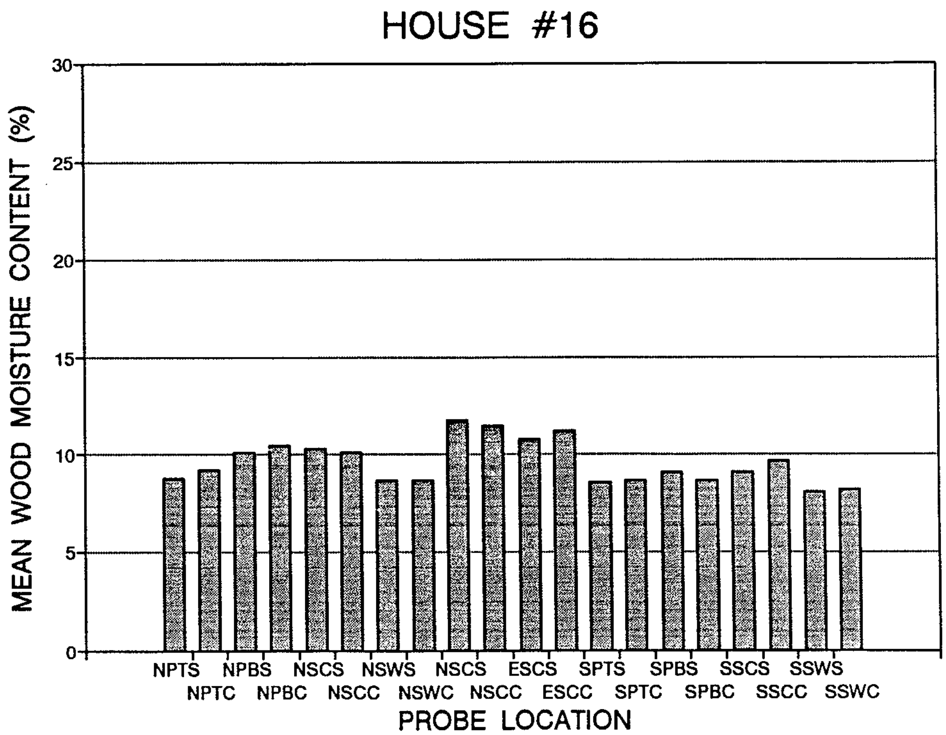


FIGURE 17(b)

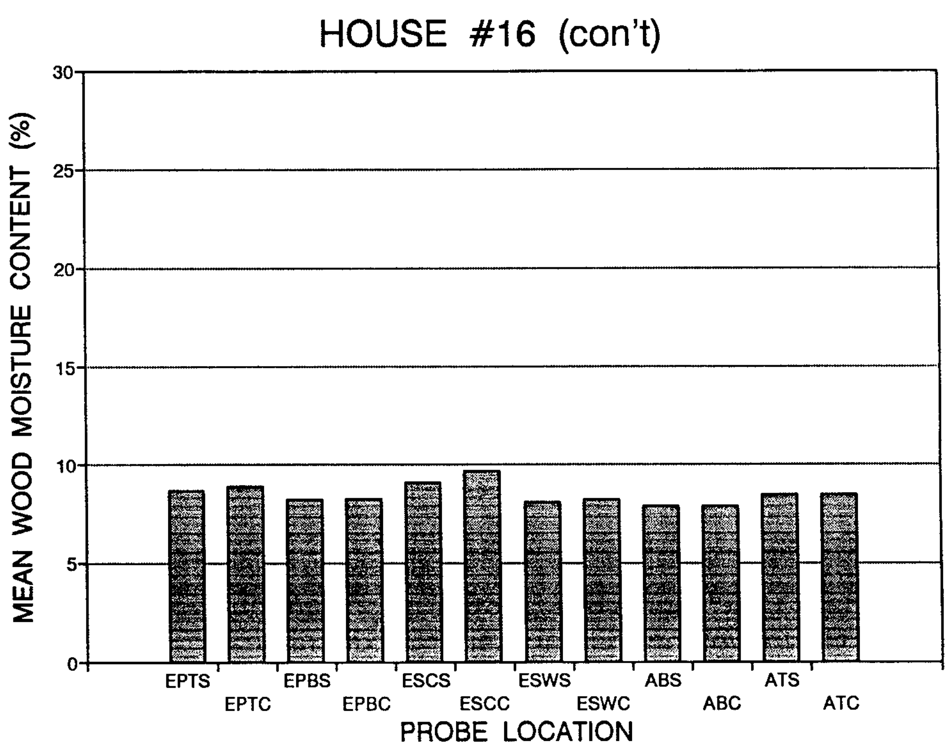


FIGURE 18

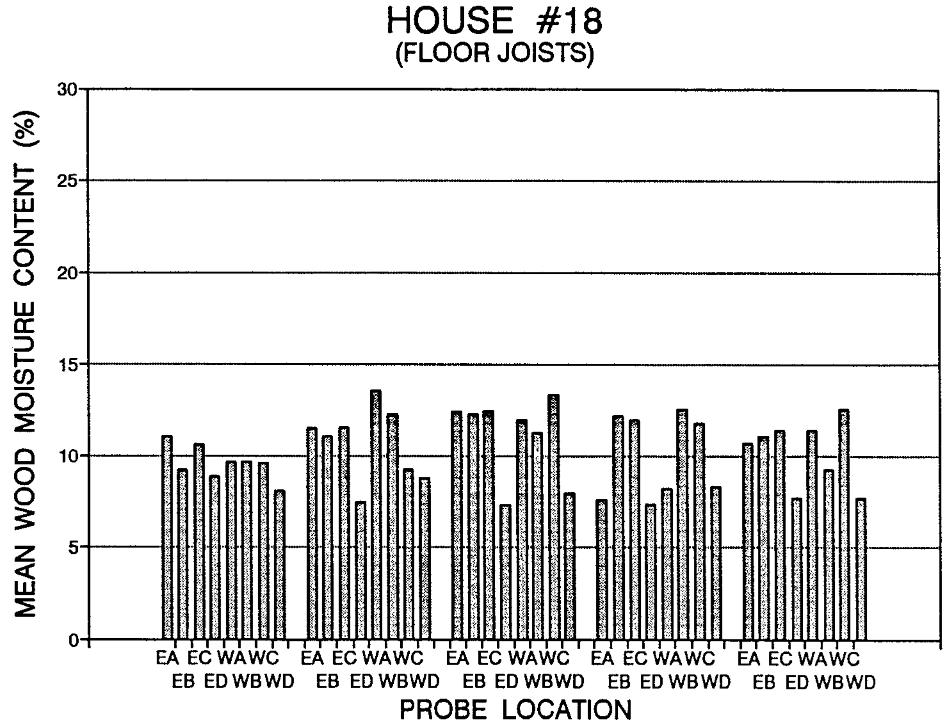


FIGURE 19(a)

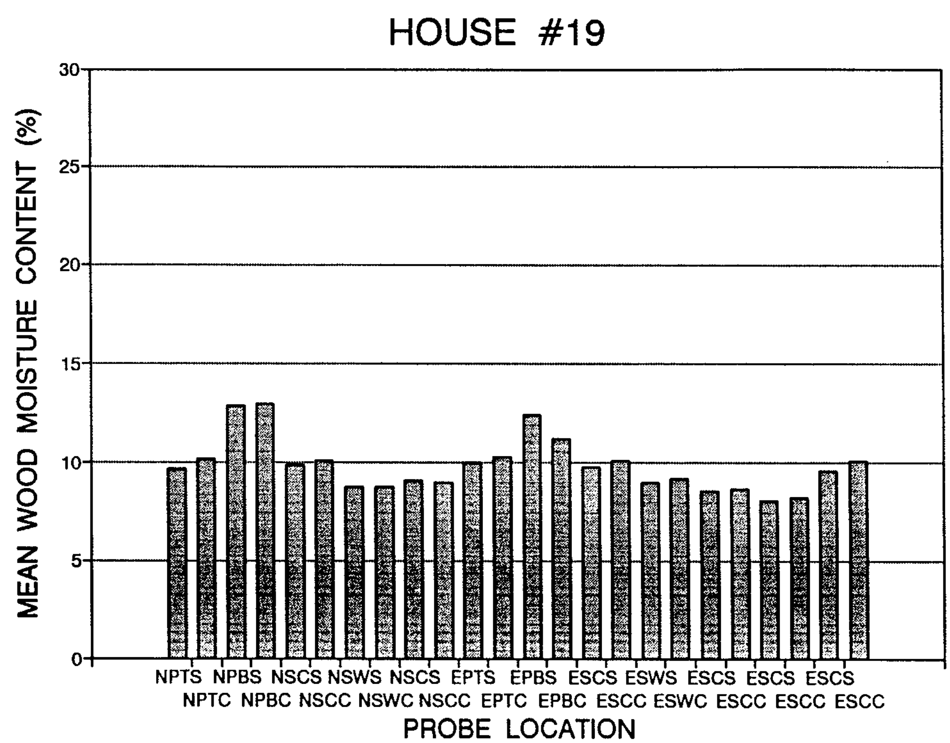


FIGURE 19(b)

HOUSE #19 (con't)

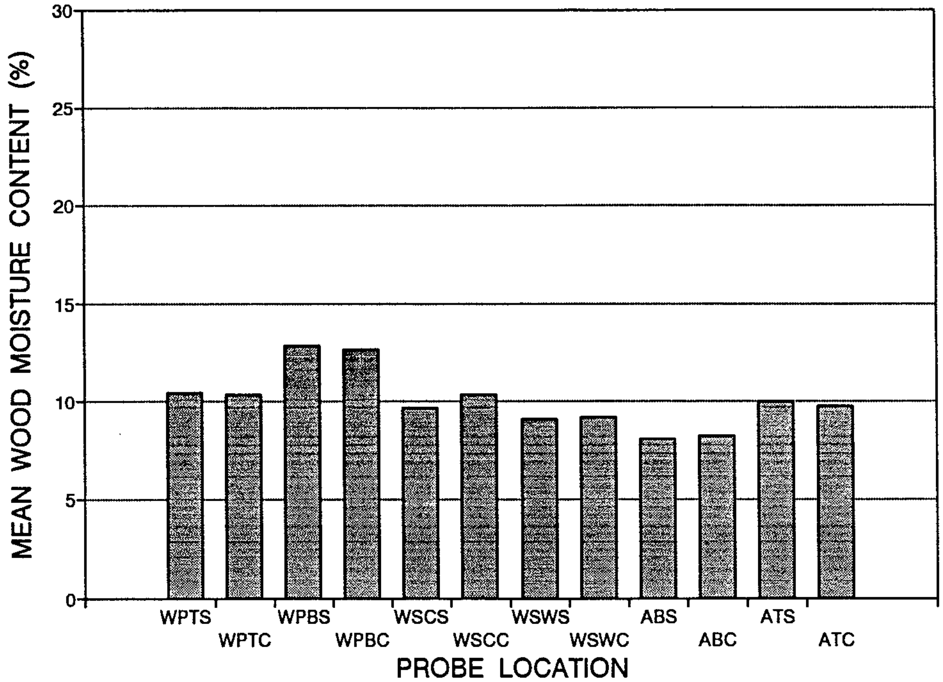


FIGURE 20(a)

HOUSE #20

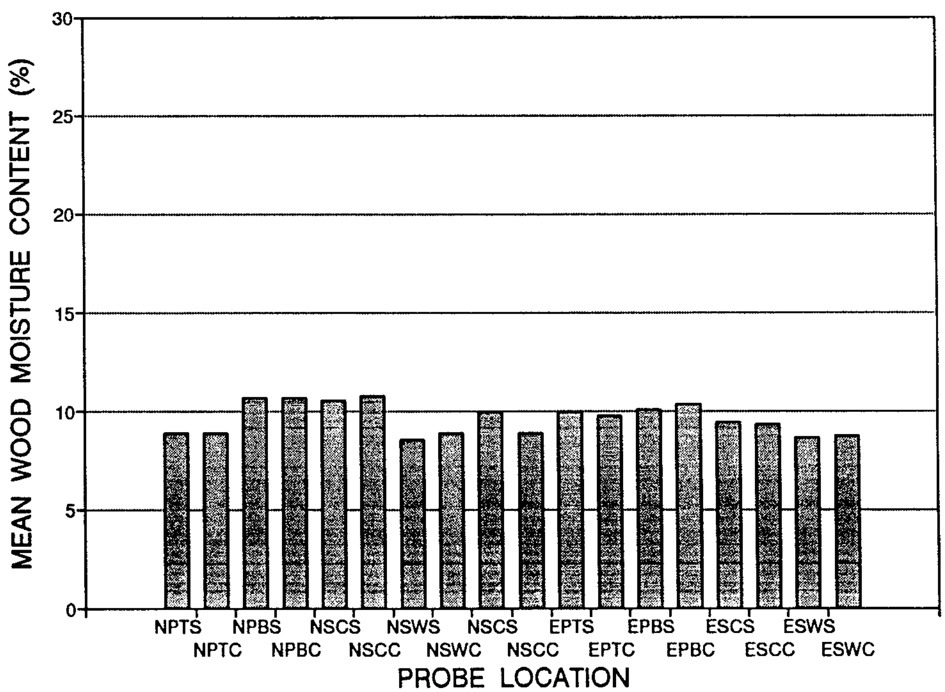


FIGURE 20(b)

HOUSE #20 (con't)

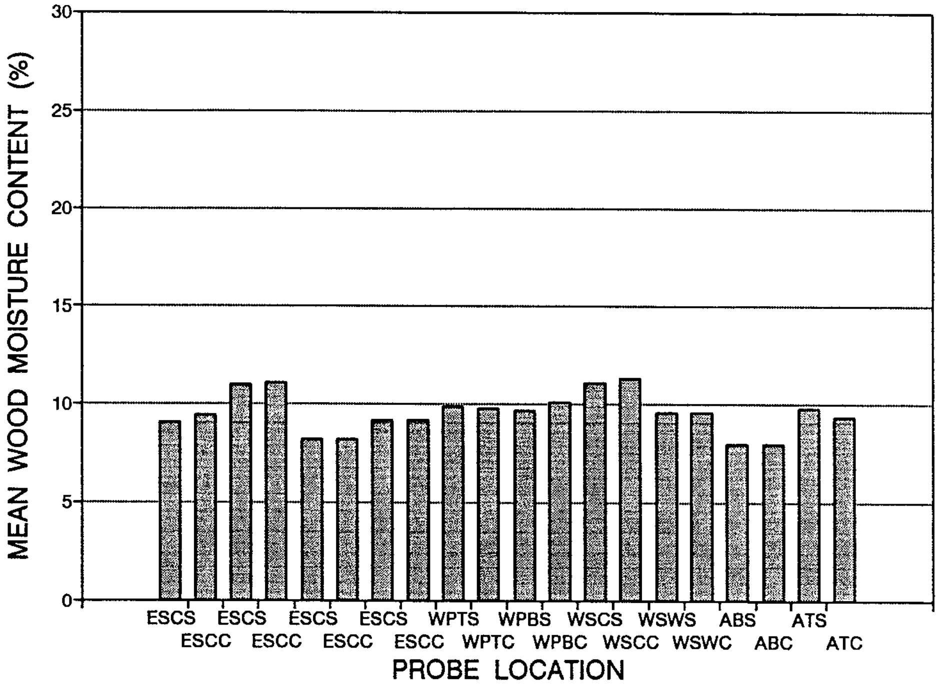


FIGURE 20(c)

HOUSE #20 (con't)
(FLOOR JOISTS)

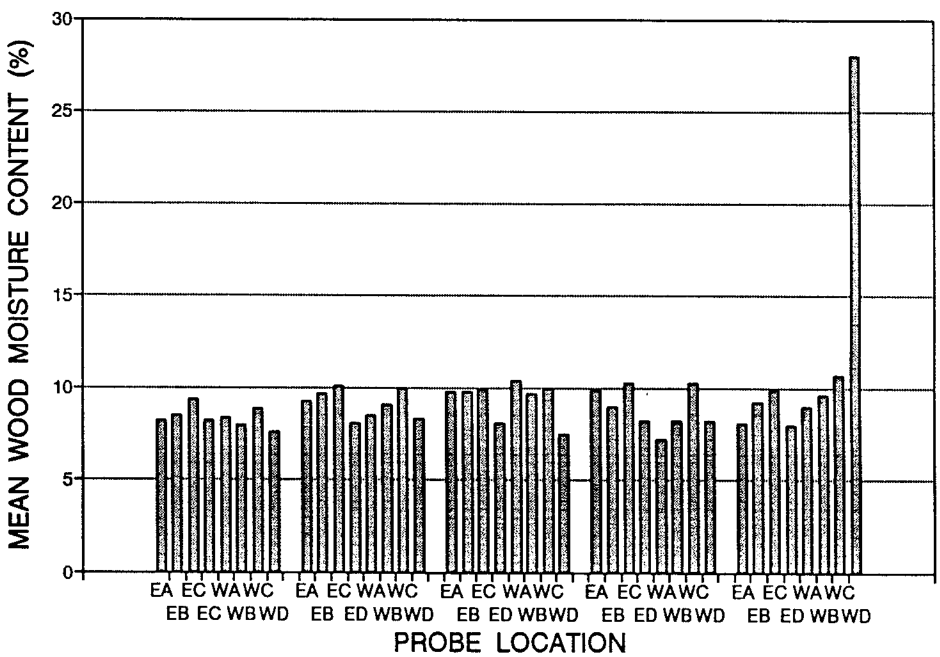


FIGURE 21(a)

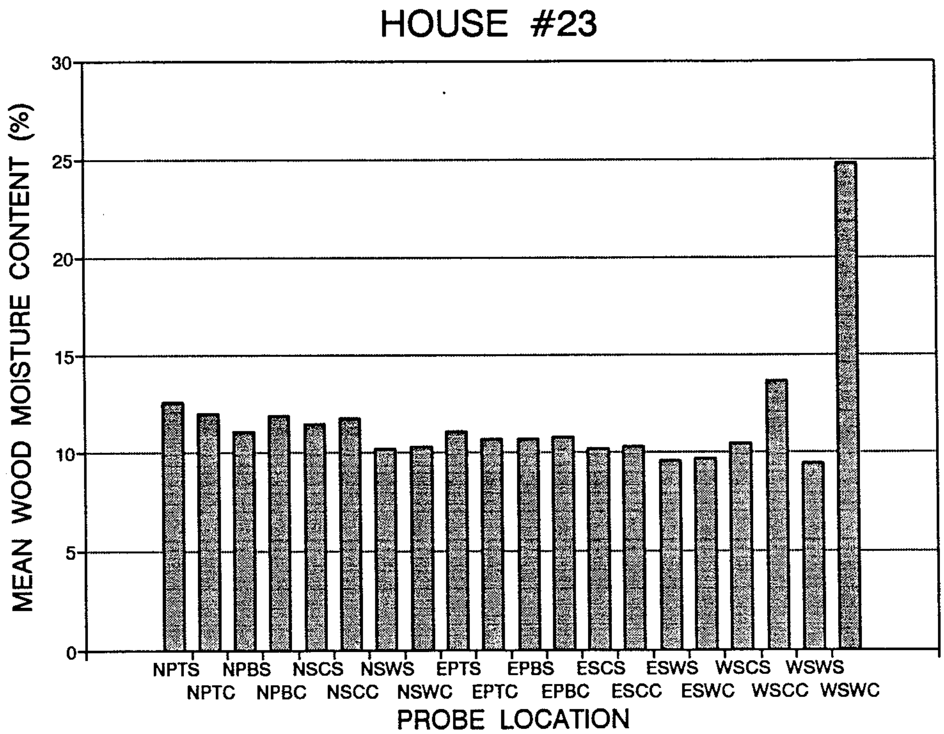
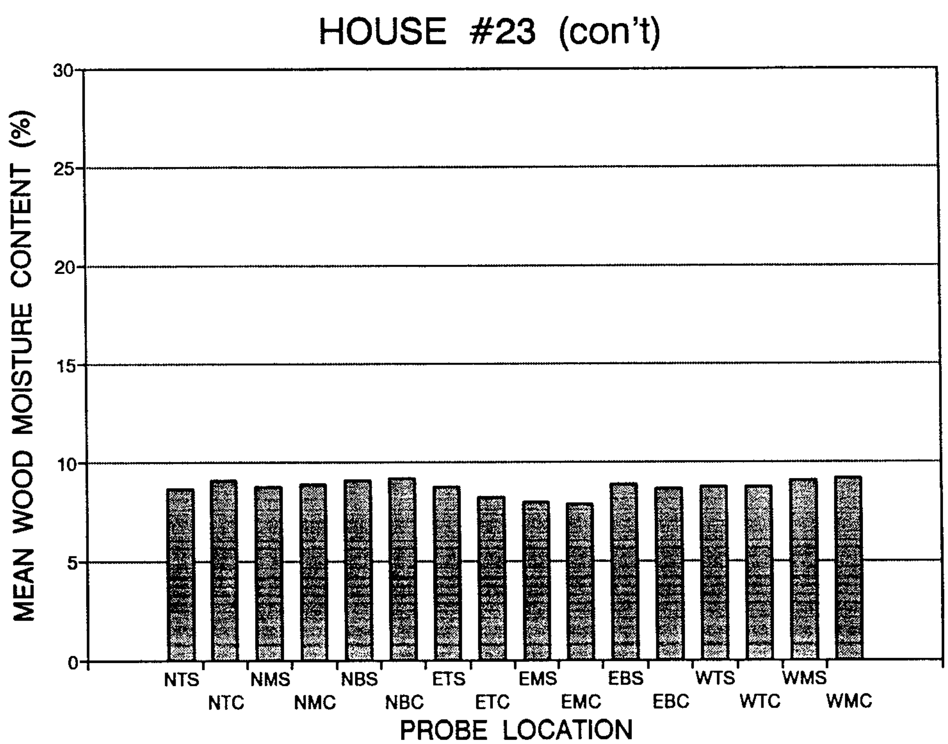


FIGURE 21(b)



SECTION 4

THERMOGRAPHIC EXAMINATIONS

4.1 METHODOLOGY

Thermographic examinations were conducted as per the schedule shown in Table 3 by Thermal Focus Inc. of Saskatoon in accordance with CGSB Standard 149-GP-2MP "Manual for Thermographic Analysis of Building Enclosures" (1986). The infrared scanning and data storage systems consisted of:

- o AGAtronics 782 Infrared Thermovision Scanning Imager, using a SW, f 1.8, 20° lens, with the display equipped with dual isotherm indicators.
- o Scan Converter 700: Imaging to signal storage interface: Viewscan Ltd.
- o Imagpac 700: Analog to digital converter with in-field digital data cartridge storage.
- o Panasonic VCR: Analog data storage.
- o Personal computer, dual diskette drive, RS-232 port.

Thermographic scans were carried out 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 15 °C (27 °F). Once 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 stations to provide a consistent vantage point. A total of 1013 thermographic images were recorded during the study.

The entire, visible main floor surface area (i.e. walls, windows, doors and ceilings) was scanned during each visit and if a thermal anomaly was identified, digital and analog records were made of its presence for later reference and analysis. Each thermal anomaly was subsequently analyzed and its type and strength assessed. Anomalies were categorized as:

- o Air infiltration/exfiltration
- o Interstitial air movement (IAM)
- o Condensation
- o Insulation anomaly
- o Thermal bridging

In many instances, faults were categorized as a combination of two or more of the above types.

Anomaly strength was classified using a three tiered rating system in which each individual anomaly was assessed a numerical value determined by comparing all thermograms of a similar or related location or feature:

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

It should be noted that the assigned rating value did not mean that the entire viewing (i.e. surface) area of the station displayed the fault, but rather that it was evident over a fraction of the area as described above.

One problem which occurred during the thermographic examinations was restricted accessibility to parts of the envelopes. In some instances, furniture was installed (that could not be readily moved) which precluded infrared examination of these areas during subsequent visits. This problem was mitigated by conducting a sub-analysis of locations visible during all thermographic examinations (see below).

4.2 FAULT COUNTS AND SEVERE FAULT ANALYSIS

Between 44 and 52 thermographic stations were defined for each house as shown in Figs. 22 and 23. Results of the thermographic analysis are summarized in Tables 7 to 9 which show the location and severity of each fault identified during each round of examinations. To quantify the extent of thermographic anomalies in each house, the concept of the "fault count" was created:

$$\text{Fault count} = (\text{No. of anomalies}) \times (\text{Average severity}) \qquad (2)$$

The thermographic results were further distilled to form a subset of viewing stations which were visible during all three examinations conducted on each house. If a station became inaccessible (due to new furniture, etc.), it was excluded from this analysis. The accessible stations were termed "continuously visible".

Since the thermographic data is fairly extensive, it was summarized into a series of Tables and Figures to aid interpretation:

Tables 10 to 12	Summarize the 1986, 1987 and 1989 thermographic examinations. The number and severity (1 to 3) of the thermographic anomalies are shown for each house along with the mean fault count.

Tables 13 to 15	Contain the same information as Tables 10 to 12 but using data from only the continuously visible stations.
Tables 16 to 18	Summarize the occurrences of severe faults (i.e. numerical value 3) for 1986, 1987 and 1989 respectively.
Tables 19 to 21	Contain the same information as Tables 16 to 18 but using data from only the continuously visible stations.

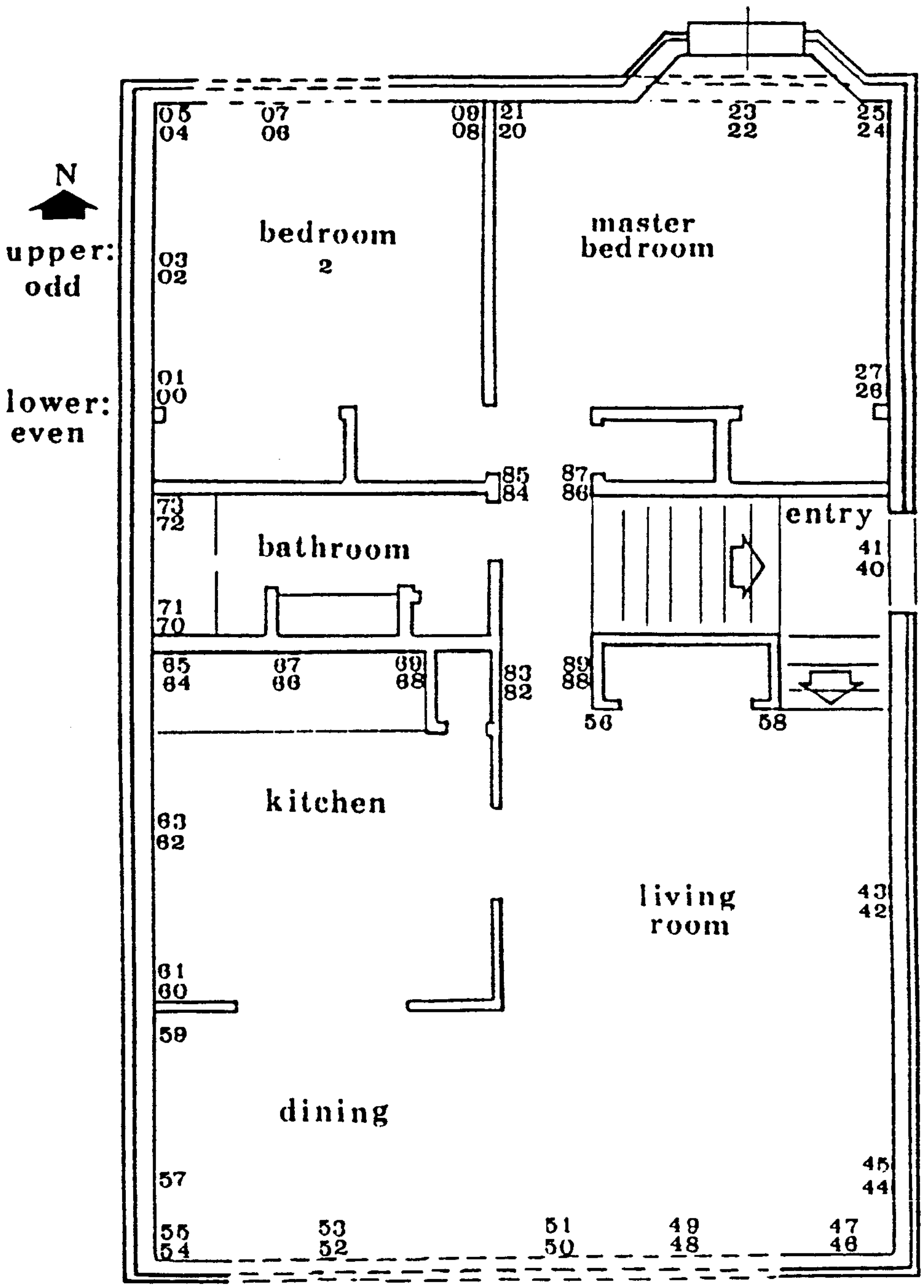
These results are also shown in Figs. 24 to 35.

This data was further refined on the basis of house type (conventional or energy efficient; and polyethylene air barrier or ADA house) to produce the mean fault count and the percentage of viewing stations with severe faults. These results are shown in Tables 22 to 25 and Figs. 36 to 43.

4.3 CLASSIFICATION OF ANOMALY TYPES

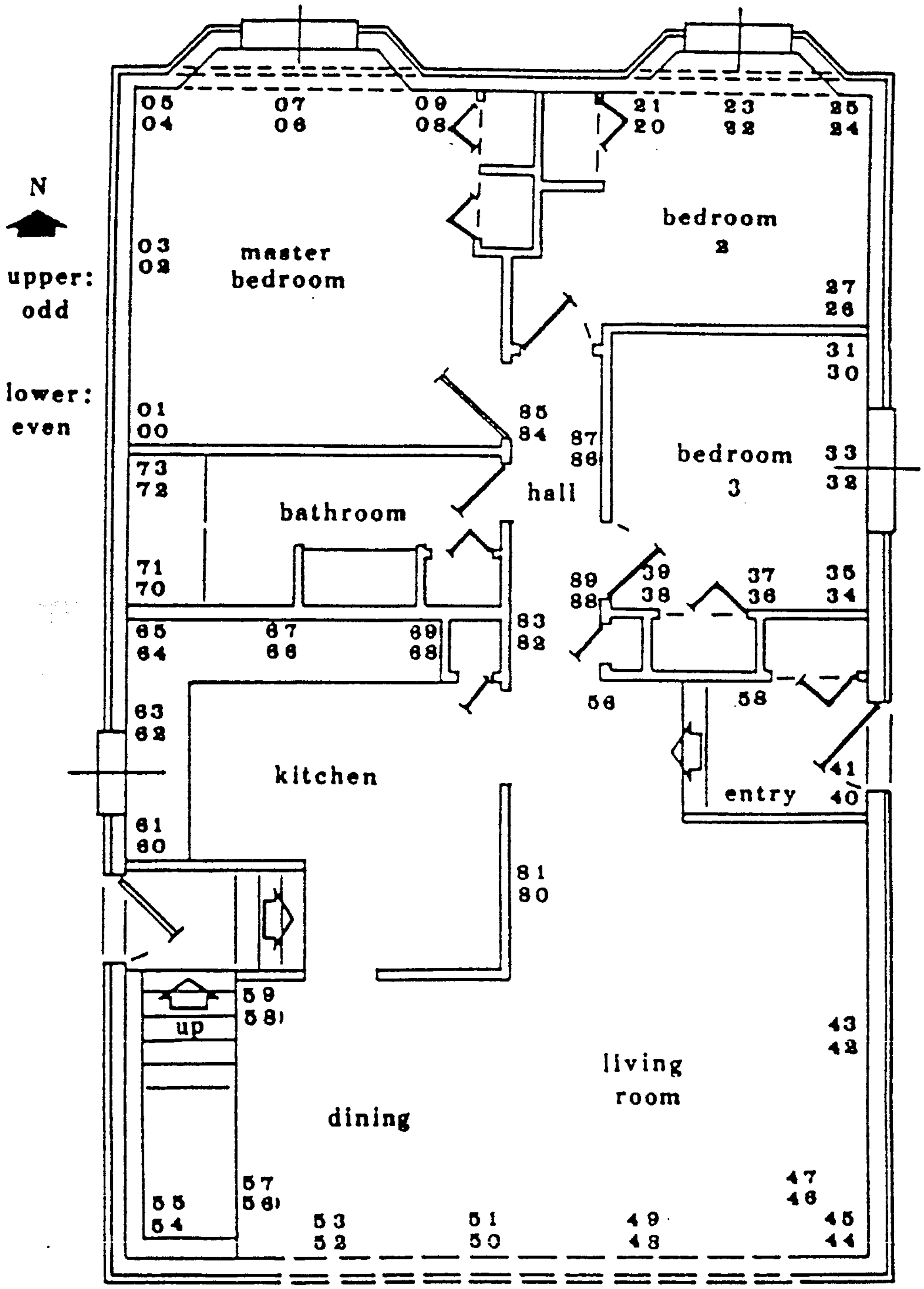
Table 26 and Fig. 44 summarize the types of thermographic faults found over the three year monitoring period.

FIGURE 22



THERMOGRAPHIC INSPECTION STATIONS
(HOUSES 1, 3, 5, 7, 9)

FIGURE 23



THERMOGRAPHIC INSPECTION STATIONS
(HOUSE 2, 4, 6, 8, 10 to 20)

TABLE 7

THERMOGRAPHIC RESULTS – 1986
FAULT SEVERITY

HOUSE	STATION																											
	00	01	02	03	04	05	06	08	09	20	21	24	25	26	27	30	31	32	33	34	35	37	39	40	41	42	43	44
1		2				1			1		2		3		2										2			
2						3		3	3		3		3				2			2	3				3			
3					2			3	2		2		2												2		1	
4		2				2		2	2	3	3	2	2		2		2				1	3	3					
5		2				2		2	3	2	2		2		1										2			
6		2				2					3	3	3				2				2				2			
7		1			1	1			1	1	2	1	1		1										2			
8		2		2		3			3		3		3			1	3				3			3	3			2
9		1			2	1		1	1		2	2	2	2	1										2	2		
10		1				2		2	2	2	3		2	2	2	2	2			2	2				2		2	2
11		2			2	2			2	2	2	2	2			2	1			2	2			2				
12	1	1	2		2	2		2	2	2	2	2	2		1	2	2			2	2			2	1			2
13	1	1	2		2	2		2	2	3	2	2	2				1				2			3	2			2
14	2				2	2		2	2	2	2	2	2	2		2	1	2		2				2	2	2		2
15					3	2		2					1											2				
16		1				1		2	1	2	1		1		1		1				1				1			
17		1				1	1	1			1		1		1						1				1			1
18					2	1						3	2			2	1			2	1				2			1
19	1	2			2	2		2	2	2	3	3	3		3	2	1			1	2			2	2			2
20		1			3	3		3	3	3	3	2	2			2	2			2	1			2	2			2
OCCURRENCES	4	15	2	1	11	19	1	14	16	11	18	11	20	3	10	8	13	1	0	8	13	1	1	8	17	2	2	9
AVG. SEVERITY	1.25	1.47	2.00	2.00	2.09	1.84	1.00	2.07	2.00	2.18	2.28	2.18	2.05	2.00	1.50	1.88	1.62	2.00	0.00	1.88	1.77	3.00	3.00	2.25	1.94	2.00	1.50	1.78
FAULT COUNT	5	22	4	2	23	35	1	29	32	24	41	24	41	6	15	15	21	2	0	15	23	3	3	18	33	4	3	16

NOTES:
1. "OCCURRENCES" is the number of houses in which an anomaly was found.
2. "AVG. SEVERITY" is the average fault severity for those houses with an anomaly present.
3. "FAULT COUNT" equals (OCCURRENCES X AVG. SEVERITY).

TABLE 7 (CON'T)

THERMOGRAPHIC RESULTS – 1986
FAULT SEVERITY

STATION																								SUMMARY		
45	46	47	48	49	50	51	53	55	56	57	58	59	61	63	65	67	69	70	71	72	73	87	89	OCCUR-RENCE	AVG. SEVERITY	FAULT COUNT
2		2				2			3	1	3	2		2					2					16	2.00	32
1					2					2			2											13	2.46	32
1						2				2		2	1		1				2					14	1.79	25
1		2		2					3	1	3	2			2		3		2			3	3	25	2.24	56
2		2		2				2				2		2				1						16	1.94	31
						2	2			3			2		3		3							14	2.43	34
1		2				1			3	2	3	2		2					2					19	1.58	30
										1									3					14	2.50	35
		2							3	1	3	1			2				1					19	1.68	32
2		1				2			3	2	3	2		2					2					25	2.04	51
	2	3	2	2						2		2							1		2			21	1.95	41
1	2	2		1						2		2							2					26	1.77	46
2	2	2		2						2						2			2					23	1.96	45
1	1	1				1				2		2				2			2					26	1.81	47
2			1							2														8	1.88	15
				1						1		1	2											15	1.20	18
	1			1						1		1	1						1					16	1.00	16
	2				3					1														13	1.77	23
2	1	2	1							2		3							2					25	2.00	50
2	1	2		2						2		2								2				23	2.13	49
13	8	12	3	8	2	6	1	1	5	19	5	14	5	4	4	2	2	1	13	1	1	1	1	371	<–TOTALS–>	708
1.54	1.50	1.92	1.33	1.63	2.50	1.67	2.00	2.00	3.00	1.68	3.00	1.86	1.60	2.00	2.00	2.00	3.00	1.00	1.85	2.00	2.00	3.00	3.00			
20	12	23	4	13	5	10	2	2	15	32	15	26	8	8	8	4	6	1	24	2	2	3	3			

TABLE 8

THERMOGRAPHIC RESULTS – 1987
FAULT SEVERITY

HOUSE	STATION																											
	00	01	02	03	04	05	06	08	09	20	21	24	25	26	27	30	31	32	33	34	35	37	39	40	41	42	43	44
1		2				1			2		2		3		2													
2						2		2	2	2	3		3				2			1	2				3			
3					2			2	2		2		3														1	
4		2				2		2	2	3	3	3	2		2		2				1	3	3					
5		2				3		2	3	2	3		2		1										2			
6		2				2			2	3	3		3				2				2				2			
7		1			2	1			1	2	1		2		1										2			
8		2		2		3			3		3		3				3				3				3			
9		2			2	2		2	1		2	2	3	2	2										2	2		
10		2				2		2	2	2	3		2		2		2			2	2				2		2	
11		1				2		1	2		2		2				1				1				1			
12		1				3		2	2	2	2	2	2		1	2	2			2	2				2			
13		1				1		2	3		2		2				1				1				2			
14						2		2	2	2	2		2								1				2			2
15						2		2		1							1				1				1			
16		1				1		2	1	1	1		1		1		1				1				1			
17		1				1		1	1		1		1		1						1				1			1
18					2			1	1								1			2	1				2			1
19		2				2		2	3	2	3		3		2	2	1			2	2				2			
20		1				3		2	3	2	3		3				2			3	2				2			
OCCURRENCES	0	15	0	1	4	18	0	16	19	12	18	3	18	1	10	2	13	0	0	6	15	1	1	0	17	1	2	3
AVG. SEVERITY	0.00	1.53	0.00	2.00	2.00	1.94	0.00	1.81	2.00	2.00	2.28	2.33	2.33	2.00	1.50	2.00	1.62	0.00	0.00	2.00	1.53	3.00	3.00	0.00	1.88	2.00	1.50	1.33
FAULT COUNT	0	23	0	2	8	35	0	29	38	24	41	7	42	2	15	4	21	0	0	12	23	3	3	0	32	2	3	4

NOTES:
1. "OCCURRENCES" is the number of houses in which an anomaly was found.
2. "AVG. SEVERITY" is the average fault severity for those houses with an anomaly present.
3. "FAULT COUNT" equals (OCCURRENCES X AVG. SEVERITY).

TABLE 8 (CON'T)

THERMOGRAPHIC RESULTS – 1987
FAULT SEVERITY

STATION																								SUMMARY		
45	46	47	48	49	50	51	53	55	56	57	58	59	61	63	65	67	69	70	71	72	73	87	89	OCCUR- RENCE	AVG. SEVERITY	FAULT COUNT
2						2			3	2	3	2		3					2					14	2.21	31
2					2					3			2											14	2.21	31
1						2				3		3			1				2					12	2.00	24
1		2		2					3	2	3				2		3		2					22	2.27	50
		3		2				2				2		2										14	2.21	31
						3	2			3			2		3		3							15	2.47	37
		2				1			3	2	3	2		2										16	1.75	28
									3	2	3								3					13	2.77	36
		3		2					3	2	3	2			2				2					20	2.15	43
1		1				2			3	2	3	2		2					1					22	2.00	44
		2		2						2		2							1		2			15	1.60	24
		2		2						2		2							2					19	1.95	37
2		2		2						2		1												14	1.71	24
2	2					1																		12	1.83	22
1										2									2					9	1.44	13
										1		1	2											14	1.14	16
1	1	1		1						1		1	1						1					18	1.00	18
																								8	1.38	11
2		2		1						2		3							3					19	2.16	41
2		1		2						2		2								2				17	2.18	37
11	2	11	0	9	1	6	1	1	6	17	6	13	4	4	4	0	2	0	11	1	1	0	0	307	<– TOTALS –>	598
1.55	1.50	1.91	0.00	1.78	2.00	1.83	2.00	2.00	3.00	2.06	3.00	1.92	1.75	2.25	2.00	0.00	3.00	0.00	1.91	2.00	2.00	0.00	0.00			
17	3	21	0	16	2	11	2	2	18	35	18	25	7	9	8	0	6	0	21	2	2	0	0			

TABLE 9

THERMOGRAPHIC RESULTS – 1989
FAULT SEVERITY

HOUSE	STATION																											
	00	01	02	03	04	05	06	08	09	20	21	24	25	26	27	30	31	32	33	34	35	37	39	40	41	42	43	44
1		1				1	2		1		2		3		2													
2						3		3	3		3		3				2				3				3			
3								2	1		2		2												1		1	
4		2				2		2	2	3	3	2	2		2		2				2	3	3		1			
5		2				2		2	3		3		2		1										2			
6		2				2			2		3		3				2				2				2			
7		1			2	1					1		1		1										2			
8		2		2		2			3		3		3			1	3				3			3	3		3	
9		2			2	1		1	1		2	2	2	2	1										1	2		
10		1				2		2	2	2	3		2				2				2				2		2	
11		1				2			2	2	2		2				2				2				1			
12		1				2		2	2	2	2	2	2		1		2			2	2				2			
13		1				1			3		2		2				1				1				1			
14						2		2	2	2	2		2				2				1				2		2	
15						2		1		1			1				1			2	1				1			
16		1				1		2	2		1		1		1		1				1				1			
17		1				1		1	1		1		1		1						1				1			
18					2	1							1				1			2	1				1			1
19		2				2		2	2	2	2		2		3		1				1				1			
20		1				3		2	3		3		3				1				2				2			
OCCURRENCES	0	15	0	1	3	19	1	13	17	7	18	3	20	1	9	1	14	0	0	3	15	1	1	1	19	1	4	1
AVG. SEVERITY	0.00	1.40	0.00	2.00	2.00	1.74	2.00	1.85	2.06	2.00	2.22	2.00	2.00	2.00	1.44	1.00	1.64	0.00	0.00	2.00	1.67	3.00	3.00	3.00	1.58	2.00	2.00	1.00
FAULT COUNT	0	21	0	2	6	33	2	24	35	14	40	6	40	2	13	1	23	0	0	6	25	3	3	3	30	2	8	1

NOTES:
1. "OCCURRENCES" is the number of houses in which an anomaly was found.
2. "AVG. SEVERITY" is the average fault severity for those houses with an anomaly present.
3. "FAULT COUNT" equals (OCCURRENCES X AVG. SEVERITY).

TABLE 9 (CON'T)

THERMOGRAPHIC RESULTS – 1989
FAULT SEVERITY

STATION																								SUMMARY		
45	46	47	48	49	50	51	53	55	56	57	58	59	61	63	65	67	69	70	71	72	73	87	89	OCCUR-RENCE	AVG. SEVERITY	FAULT COUNT
1		1				2			3	2	3	1		2					2					16	1.81	29
1					2					2			2											12	2.50	30
1						1				2		2	1		1				2					13	1.46	19
		2		2					3	2	3	2			2		3		2					23	2.26	52
		2		2				2				2		2										13	2.08	27
						3	2			3			2		3		3							14	2.43	34
1		2							3	1	3	1		2					2					15	1.60	24
						3			3	2	3								3					17	2.65	45
		2		2					3	1	3	1			2		1							20	1.70	34
2		2				2			3	2	3	2		2										19	2.11	40
		2		2						2		1									2			14	1.79	25
2		2		1						2		2					2							19	1.84	35
2		2		2						1		1												13	1.54	20
2						1																		12	1.83	22
1										1									2					11	1.27	14
										1		1	2											13	1.23	16
1		1		1						1		1	1						1					16	1.00	16
	2				2	1																		11	1.36	15
1		1		1						2		2							2					17	1.71	29
2		1		2						1		2								1				15	1.93	29
12	1	12	0	9	2	7	1	1	6	17	6	14	5	4	4	0	4	0	8	1	1	0	0	303	<– TOTALS –>	555
1.42	2.00	1.67	0.00	1.67	2.00	1.86	2.00	2.00	3.00	1.65	3.00	1.50	1.60	2.00	2.00	0.00	2.25	0.00	2.00	1.00	2.00	0.00	0.00			
17	2	20	0	15	4	13	2	2	18	28	18	21	8	8	8	0	9	0	16	1	2	0	0			

TABLE 10

THERMOGRAPHIC FAULT SUMMARY, ALL VISIBLE ANOMALIES - 1986

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	19	1.58	30
8	14	2.50	35
9	19	1.68	32
10	25	2.04	51
TOTAL	77		148
MEAN	19.3	1.95	37.0

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	16	2.00	32
2	13	2.46	32
3	14	1.79	25
4	25	2.24	56
5	16	1.94	31
6	14	2.43	34
11	21	1.95	41
12	26	1.77	46
13	23	1.96	45
14	26	1.81	47
15	8	1.88	15
16	15	1.20	18
17	16	1.00	16
18	13	1.77	23
19	25	2.00	50
20	23	2.13	49
TOTAL	294		560
MEAN	18.4	1.89	35.0

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 11

THERMOGRAPHIC FAULT SUMMARY, ALL VISIBLE ANOMALIES - 1987

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	16	1.75	28
8	13	2.77	36
9	20	2.15	43
10	22	2.00	44
TOTAL	71		151
MEAN	17.8	2.17	37.8

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	14	2.21	31
2	14	2.21	31
3	12	2.00	24
4	22	2.27	50
5	14	2.21	31
6	15	2.47	37
11	15	1.60	24
12	19	1.95	37
13	14	1.71	24
14	12	1.83	22
15	9	1.44	13
16	14	1.14	16
17	18	1.00	18
18	8	1.38	11
19	19	2.16	41
20	17	2.18	37
TOTAL	236		447
MEAN	14.8	1.86	27.9

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 12

THERMOGRAPHIC FAULT SUMMARY, ALL VISIBLE ANOMALIES - 1989

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	15	1.60	24
8	17	2.65	45
9	20	1.70	34
10	19	2.11	40
TOTAL	71		143
MEAN	17.8	2.01	35.8

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	16	1.81	29
2	12	2.50	30
3	13	1.46	19
4	23	2.26	52
5	13	2.08	27
6	14	2.43	34
11	14	1.79	25
12	19	1.84	35
13	13	1.54	20
14	12	1.83	22
15	11	1.27	14
16	13	1.23	16
17	16	1.00	16
18	11	1.36	15
19	17	1.71	29
20	15	1.93	29
TOTAL	232		412
MEAN	14.5	1.75	25.8

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 13

THERMOGRAPHIC FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1986

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	13	1.77	23
8	11	2.64	29
9	18	1.72	31
10	19	2.05	39
TOTAL	61		122
MEAN	15.3	2.05	30.5

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	14	2.00	28
2	12	2.50	30
3	11	1.82	20
4	22	2.18	48
5	14	2.00	28
6	13	2.38	31
11	12	1.92	23
12	17	1.76	30
13	12	1.83	22
14	9	1.78	16
15	4	2.00	8
16	14	1.14	16
17	13	1.00	13
18	8	1.50	12
19	17	2.12	36
20	14	2.14	30
TOTAL	206		391
MEAN	12.9	1.88	24.4

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 14

THERMOGRAPHIC FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1987

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	14	1.79	25
8	13	2.77	36
9	19	2.16	41
10	20	2.05	41
TOTAL	66		143
MEAN	16.5	2.19	35.8

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	14	2.21	31
2	13	2.31	30
3	12	2.00	24
4	22	2.27	50
5	14	2.21	31
6	15	2.47	37
11	14	1.64	23
12	17	1.94	33
13	13	1.69	22
14	10	1.80	18
15	9	1.44	13
16	13	1.15	15
17	16	1.00	16
18	8	1.38	11
19	18	2.17	39
20	15	2.13	32
TOTAL	223		425
MEAN	13.9	1.86	26.6

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 15

THERMOGRAPHIC FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1989

CONVENTIONAL HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
7	13	1.62	21
8	15	2.73	41
9	20	1.70	34
10	19	2.11	40
TOTAL	67		136
MEAN	16.8	2.04	34.0

ENERGY EFFICIENT HOUSES			
HOUSE	OCCURRENCES	AVERAGE SEVERITY	FAULT COUNT
1	15	1.87	28
2	12	2.50	30
3	11	1.55	17
4	22	2.27	50
5	13	2.08	27
6	14	2.43	34
11	13	1.54	23
12	18	1.83	33
13	13	1.54	20
14	11	1.82	20
15	10	1.30	13
16	13	1.23	16
17	16	1.00	16
18	9	1.22	11
19	17	1.71	29
20	15	1.93	29
TOTAL	222		396
MEAN	13.9	1.75	24.8

FAULT COUNT = (No. of Occurrences) x (Average Severity)

TABLE 16

SEVERE FAULT SUMMARY, ALL VISIBLE STATIONS - 1986

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	9	17
9	2	5
10	3	6
TOTAL	16	
MEAN	4.0	8.0%

ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	3	7
2	7	13
3	1	2
4	9	17
5	1	2
6	6	12
11	1	2
12	0	0
13	2	4
14	0	0
15	1	2
16	0	0
17	0	0
18	2	4
19	5	10
20	6	12
TOTAL	44	
MEAN	2.8	5.4%

TABLE 17

SEVERE FAULT SUMMARY, ALL VISIBLE STATIONS - 1987

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	10	19
9	4	9
10	3	6
TOTAL	19	
MEAN	4.8	9.7%

ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	4	9
2	4	8
3	3	7
4	8	15
5	4	9
6	7	13
11	0	0
12	1	2
13	1	2
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	5	10
20	5	10
TOTAL	42	
MEAN	2.6	5.3%

TABLE 18

SEVERE FAULT SUMMARY, ALL VISIBLE STATIONS - 1989

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	12	23
9	2	5
10	3	6
TOTAL	19	
MEAN	4.8	9.5%

ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	3	7
2	7	13
3	0	0
4	7	13
5	2	5
6	6	12
11	0	0
12	0	0
13	1	2
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	1	2
20	4	8
TOTAL	31	
MEAN	1.9	3.8%

TABLE 19

SEVERE FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1986

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	8	15
9	2	5
10	3	6
TOTAL	15	
MEAN	3.8	7.6%

ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	3	7
2	7	13
3	1	2
4	7	13
5	1	2
6	5	10
11	1	2
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	4	8
20	4	8
TOTAL	33	
MEAN	2.1	4.1%

TABLE 20

SEVERE FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1987

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	10	19
9	4	9
10	3	6
TOTAL	19	
MEAN	4.8	9.7%

ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	4	9
2	4	8
3	3	7
4	8	15
5	4	9
6	7	13
11	0	0
12	1	2
13	1	2
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	5	10
20	4	8
TOTAL	41	
MEAN	2.6	5.2%

TABLE 21

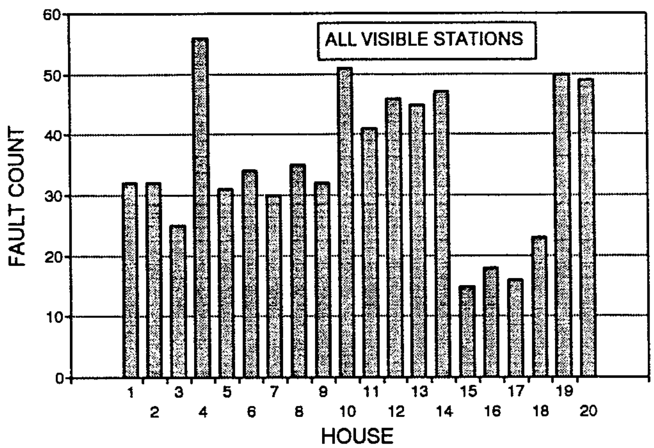
SEVERE FAULT SUMMARY, CONTINUOUSLY VISIBLE STATIONS - 1989

CONVENTIONAL HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
7	2	5
8	11	21
9	2	5
10	3	6
TOTAL	18	
MEAN	4.5	9.0%

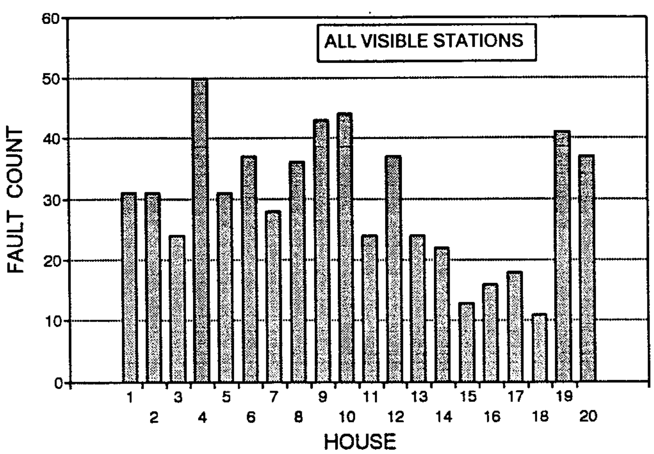
ENERGY EFFICIENT HOUSES		
HOUSE	NO. OF SEVERE FAULTS	PERCENTAGE OF STATIONS WITH SEVERE FAULTS
1	3	7
2	7	13
3	0	0
4	7	13
5	2	5
6	6	12
11	0	0
12	0	0
13	1	2
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	1	2
20	4	8
TOTAL	31	
MEAN	1.9	3.8%

FIGURES 24, 25 and 26

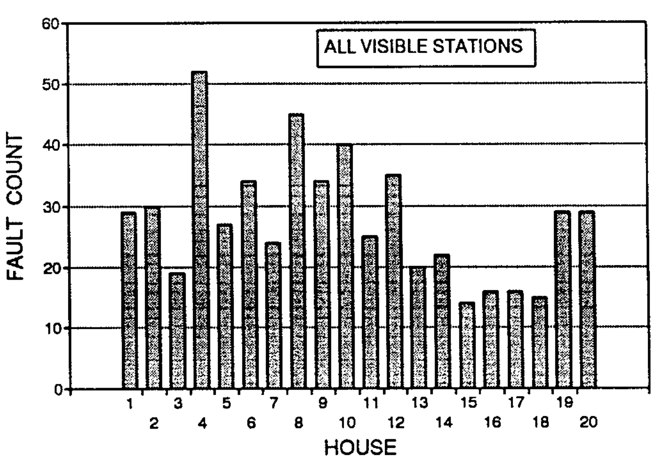
1986



1987

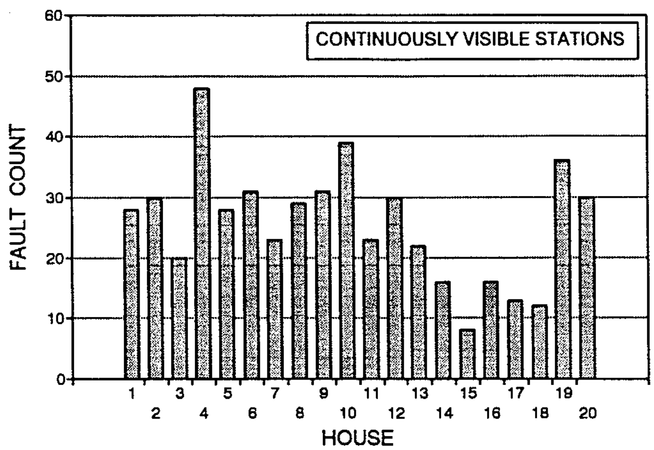


1989

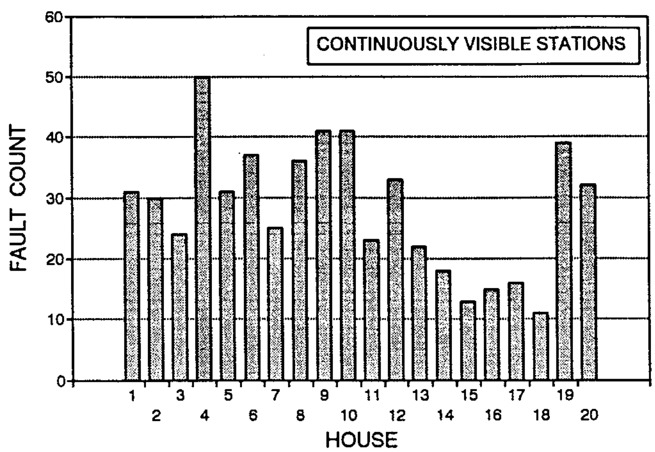


FIGURES 27, 28 and 29

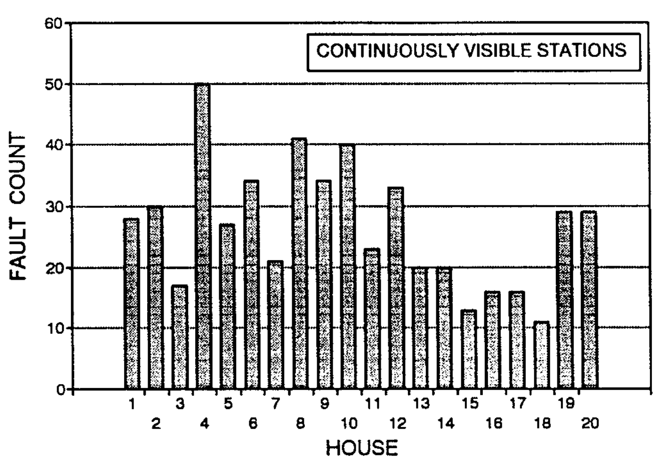
1986



1987

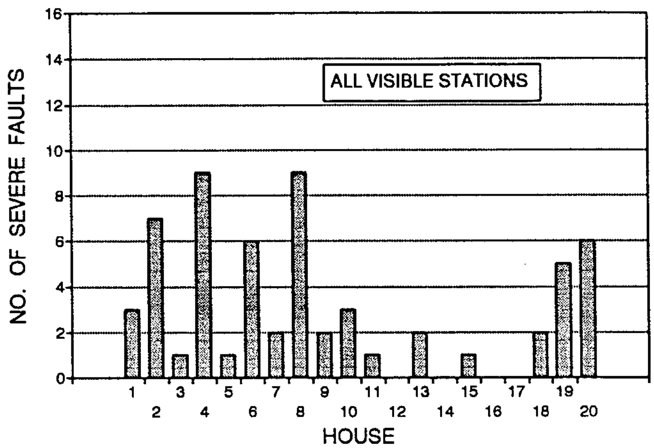


1989

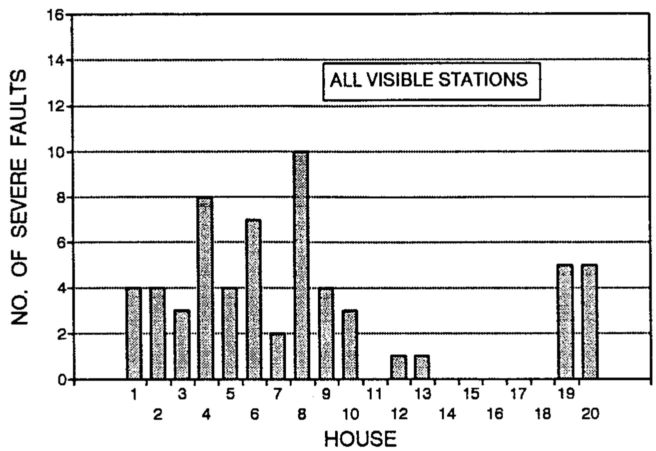


FIGURES 30, 31 and 32

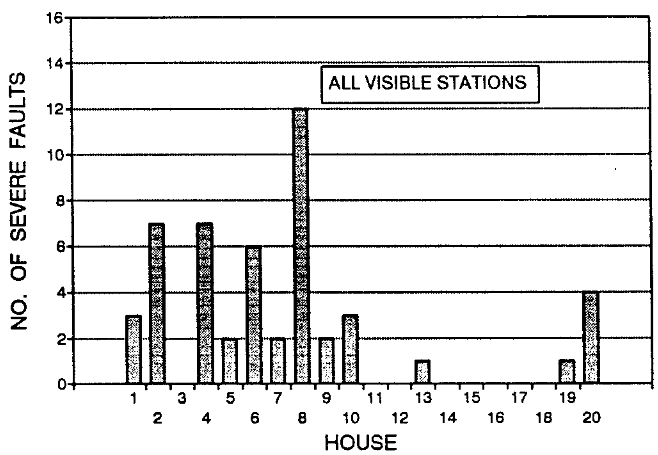
1986



1987

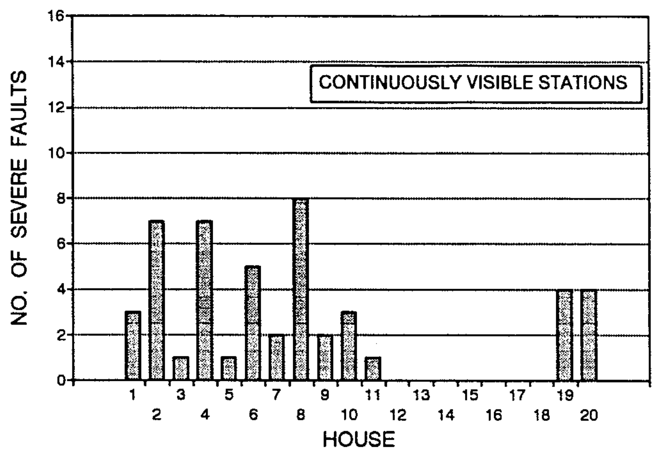


1989

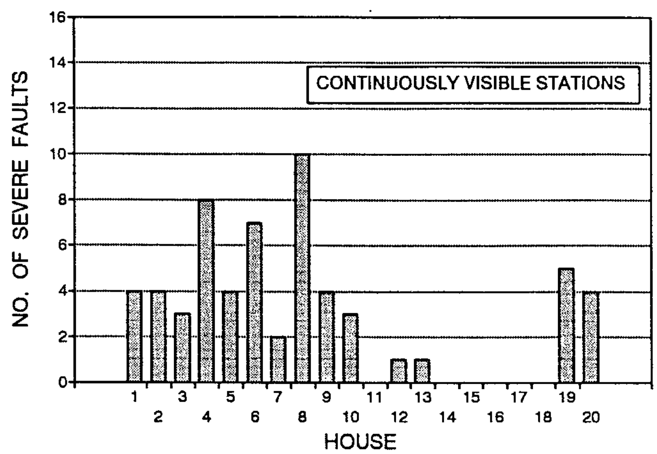


FIGURES 33, 34 and 35

1986



1987



1989

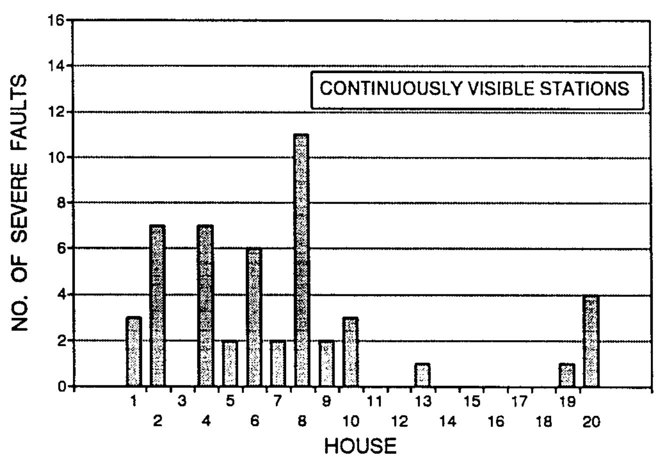


TABLE 22

MEAN FAULT COUNT SUMMARY

ALL VISIBLE STATIONS

YEAR	MEAN FAULT COUNT					
	CONVENTIONAL			ENERGY EFFICIENT		
	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

YEAR	MEAN FAULT COUNT					
	CONVENTIONAL			ENERGY EFFICIENT		
	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 23

SEVERE FAULT SUMMARY

ALL VISIBLE STATIONS

YEAR	PERCENTAGE OF STATIONS WITH SEVERE FAULTS					
	CONVENTIONAL			ENERGY EFFICIENT		
	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

YEAR	PERCENTAGE OF STATIONS WITH SEVERE FAULTS					
	CONVENTIONAL			ENERGY EFFICIENT		
	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 24

MEAN FAULT COUNT SUMMARY

ALL VISIBLE STATIONS

YEAR	MEAN FAULT COUNT					
	POLYETHYLENE			ADA		
	CONVENTIONAL	ENERGY EFFICIENT	ALL	CONVENTIONAL	ENERGY EFFICIENT	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

YEAR	MEAN FAULT COUNT					
	POLYETHYLENE			ADA		
	CONVENTIONAL	ENERGY EFFICIENT	ALL	CONVENTIONAL	ENERGY EFFICIENT	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 25

SEVERE FAULT SUMMARY

ALL VISIBLE STATIONS

YEAR	PERCENTAGE OF STATIONS WITH SEVERE FAULTS					
	POLYETHYLENE			ADA		
	CONVENTIONAL	ENERGY EFFICIENT	ALL	CONVENTIONAL	ENERGY EFFICIENT	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

YEAR	PERCENTAGE OF STATIONS WITH SEVERE FAULTS					
	POLYETHYLENE			ADA		
	CONVENTIONAL	ENERGY EFFICIENT	ALL	CONVENTIONAL	ENERGY EFFICIENT	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

FIGURE 36

ALL VISIBLE STATIONS

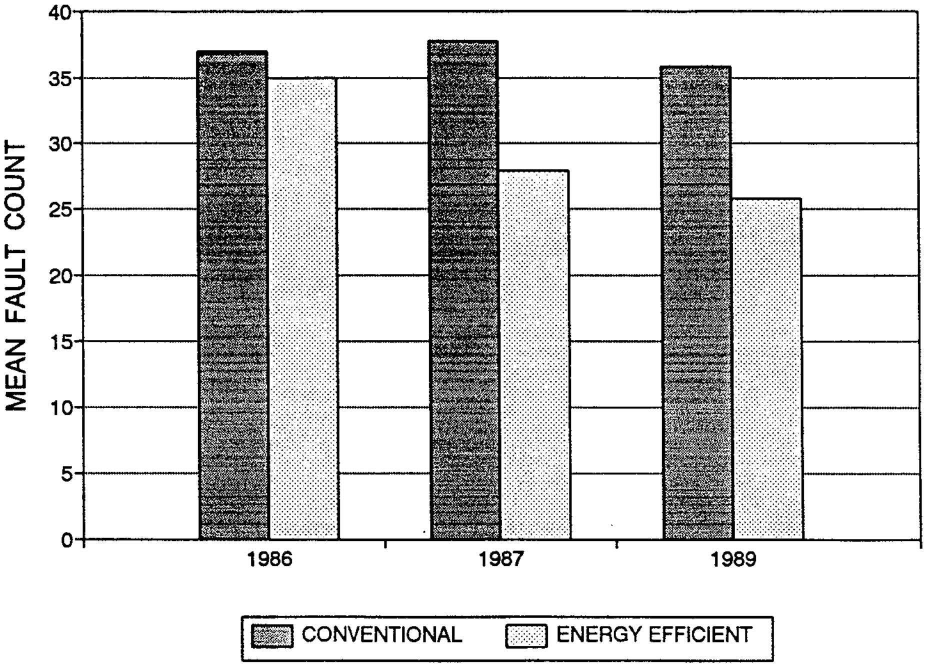


FIGURE 37

CONTINUOUSLY VISIBLE STATIONS

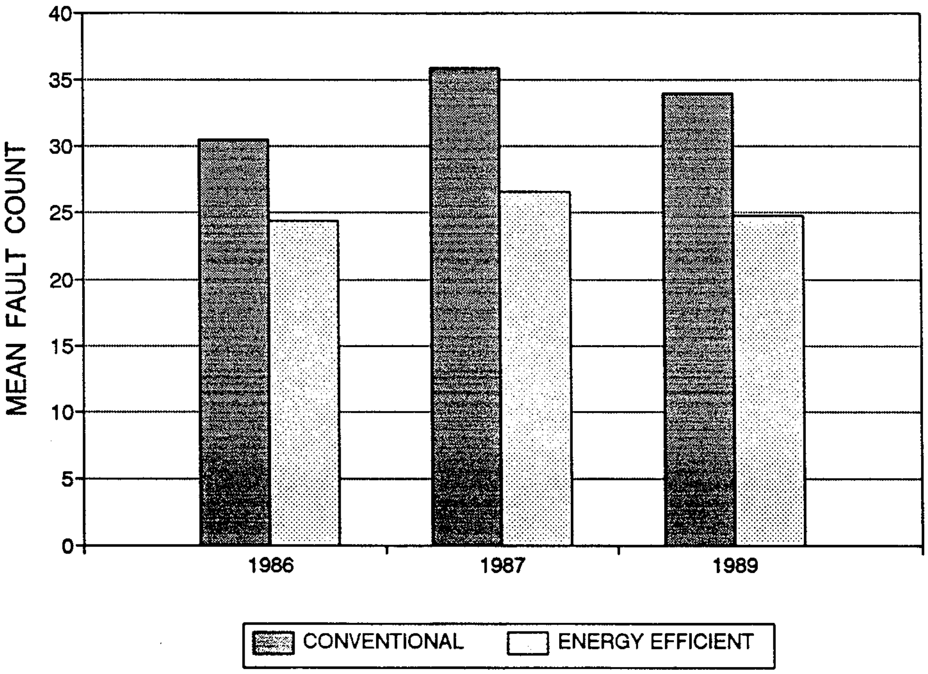


FIGURE 38

ALL VISIBLE STATIONS

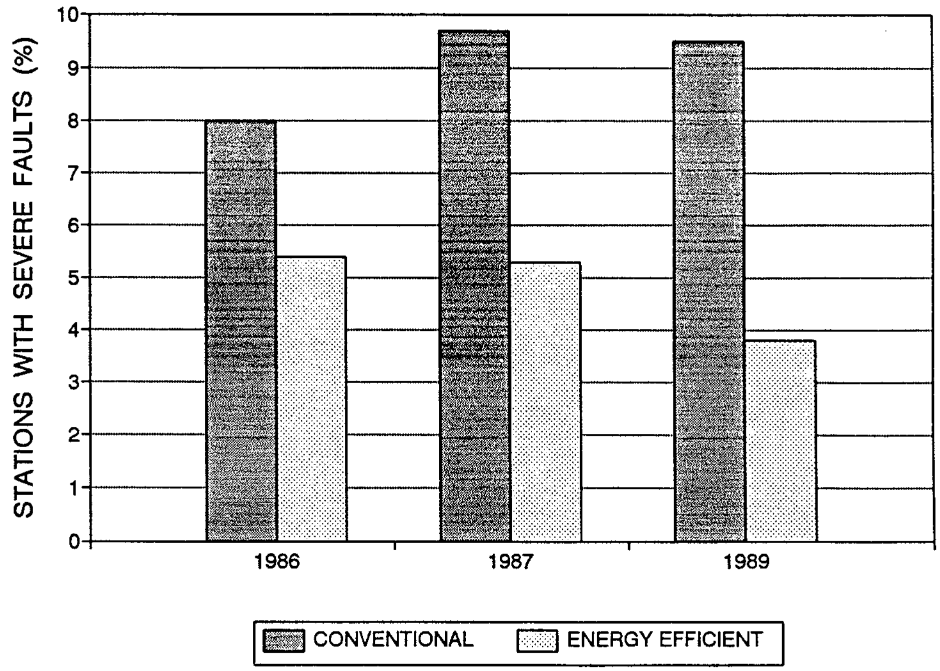


FIGURE 39

CONTINUOUSLY VISIBLE STATIONS

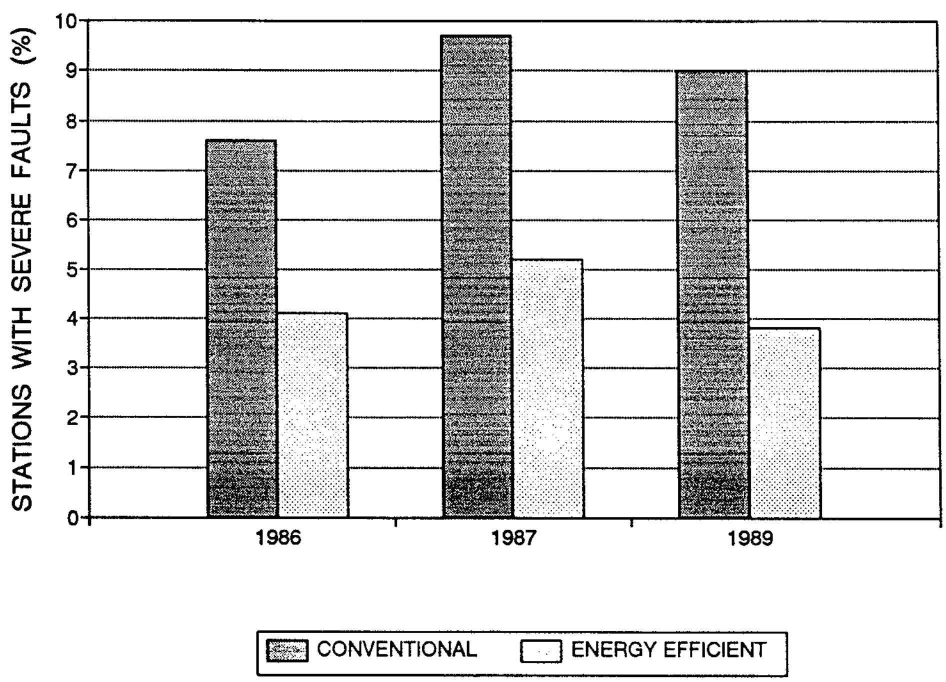


FIGURE 40

ALL VISIBLE STATIONS

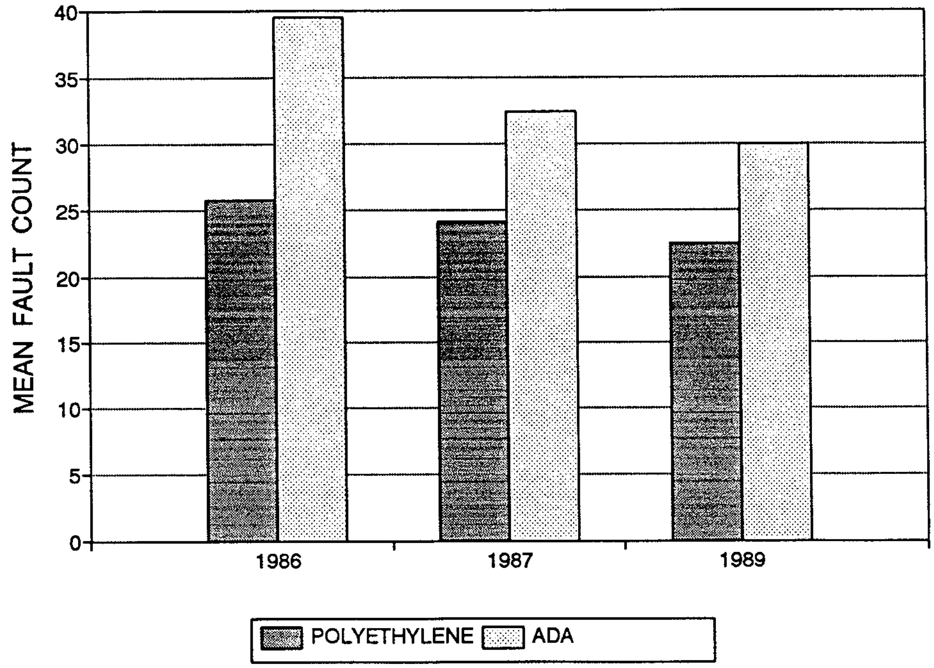


FIGURE 41

CONTINUOUSLY VISIBLE STATIONS

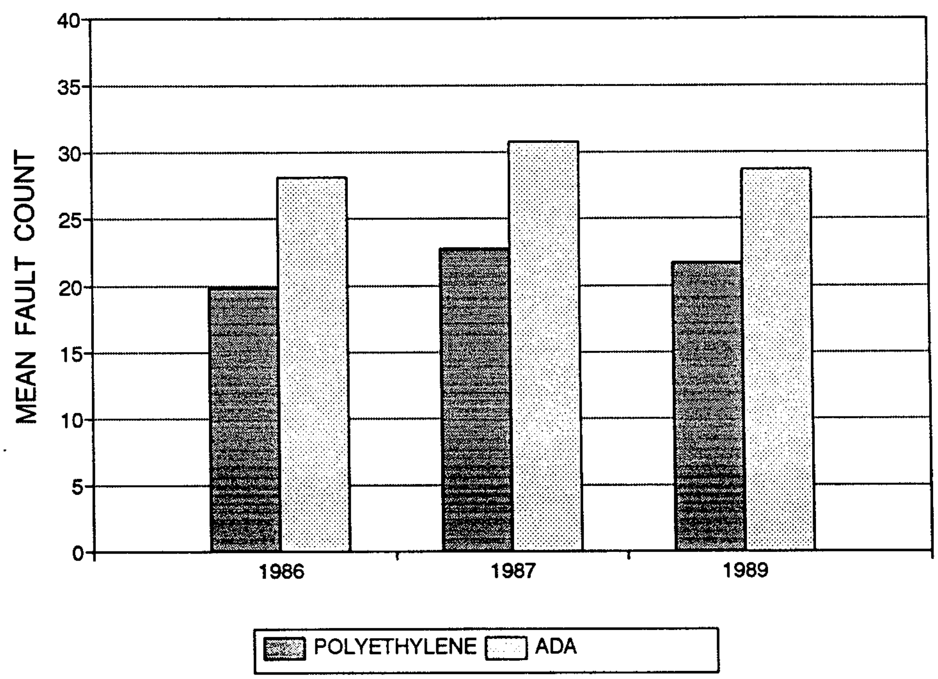


FIGURE 42

ALL VISIBLE STATIONS

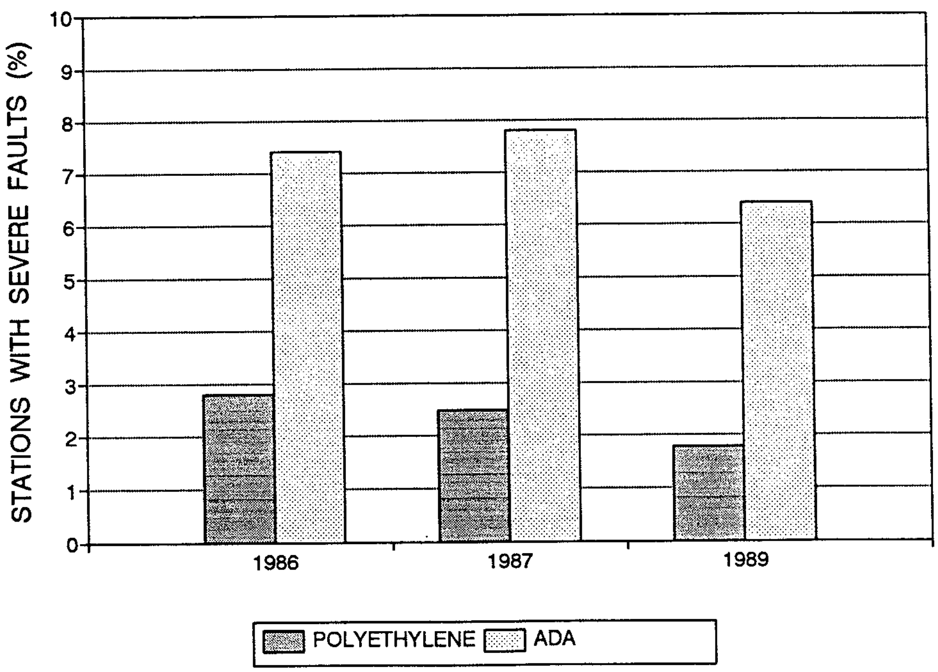


FIGURE 43

CONTINUOUSLY VISIBLE STATIONS

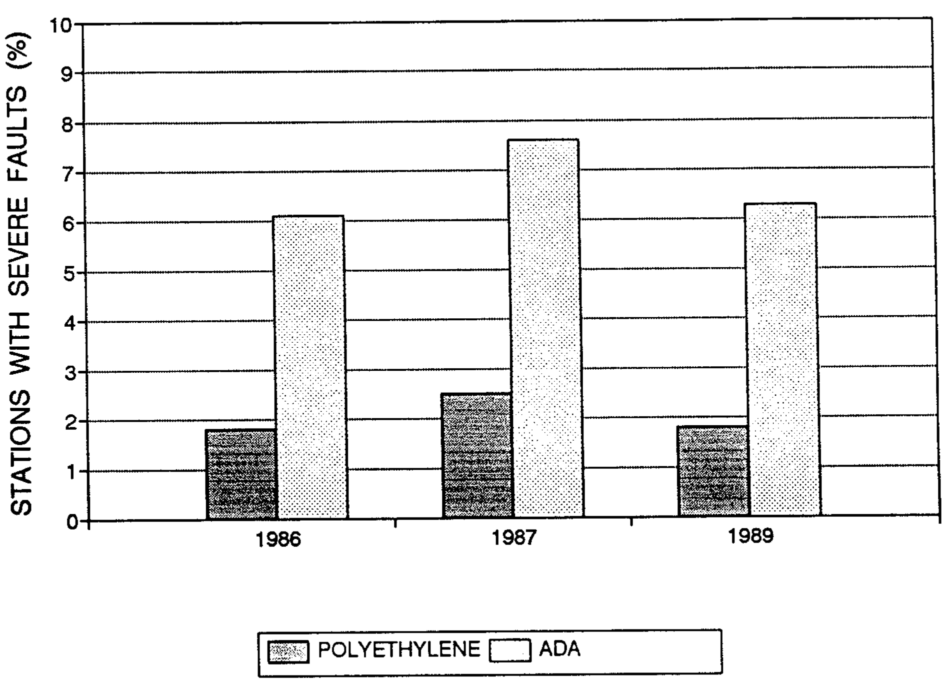


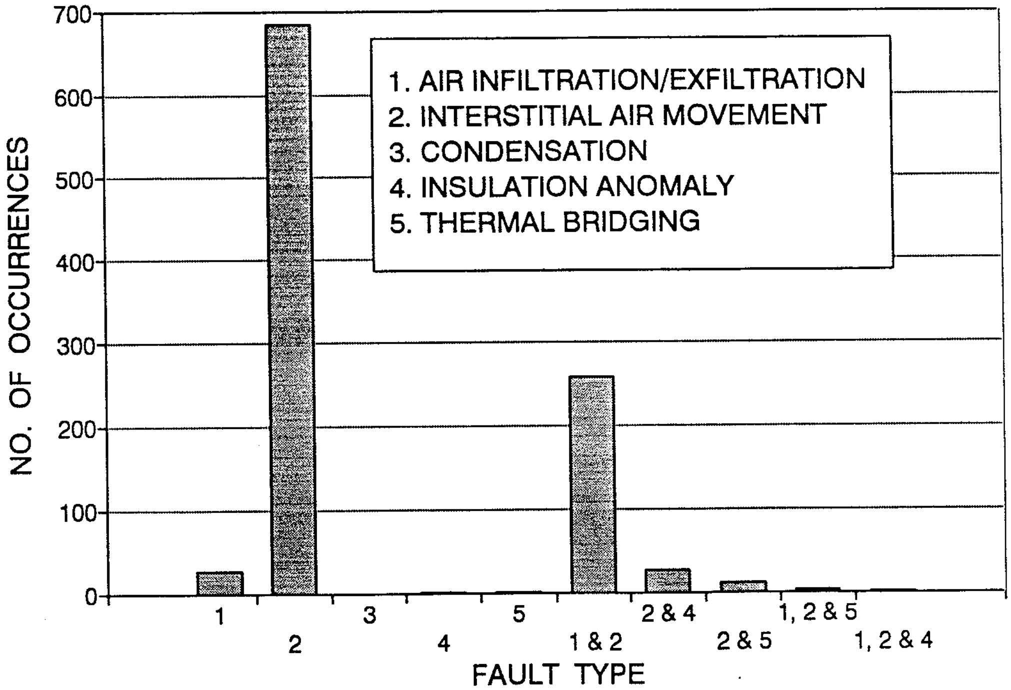
TABLE 26

SUMMARY OF THERMOGRAPHIC FAULT TYPES (ALL HOUSES)

FAULT TYPE	NO. OF OCCURRENCES	%
1. Air Infiltration/Exfiltration	26	2.6
2. Interstitial Air Movement	684	67.5
3. Condensation	0	0.0
4. Insulation Anomaly	1	0.1
5. Thermal Bridging	1	0.1
Combination 1 + 2	259	25.6
Combination 2 + 4	27	2.7
Combination 2 + 5	11	1.1
Combination 1, 2 + 5	3	0.3
Combination 1, 2 + 4	1	0.1
TOTAL	1013	100.0

FIGURE 44

FAULT TYPE SUMMARY - ALL 3 YEARS



SECTION 5

AIRTIGHTNESS

5.1 METHODOLOGY

Airtightness tests were conducted on a regular basis during the monitoring program in accordance with CAN/CGSB 149.10-M86 "Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method" (1986). This method involves measuring the air leakage rate of the building at various indoor-to-outdoor pressure differentials ranging from 15 Pa to 50 Pa and fitting a regression curve to the data from which the airtightness can be expressed as a leakage parameter at a specified pressure differential. The primary application of the airtightness test results was to determine if significant air barrier degradation had taken place. A total of 167 airtightness tests were performed during the study. Results are discussed in more detail in a separate report (Proskiw 1992).

To evaluate changes in airtightness, specifically degradation caused by air barrier deterioration, four analysis methods were used:

1. Visual examinations - A visual examination of the airtightness vs. time plot was made for each house to identify any changes in leakage.

2. 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. This method had the disadvantages of relying on only two measurements and of being susceptible to seasonally induced variations in airtightness if the tests were performed during different periods of the year.

3. Variation between the first and last seasonally coincident airtightness tests - Similar to Method 2, except the seasonal impact was eliminated by using seasonally coincident data.

4. Statistical tests - Degradation of airtightness was assessed by determining whether a relationship existed between two parameters: airtightness and time. This concept can be expressed mathematically (using the air change rate at 50 Pa data as an example) with a regression equation of the form:

$$ac/hr_{50} = \alpha + \beta(t) \quad (3)$$

where:
α = Initial ac/hr_{50} at the start of the monitoring period
β = Slope of the regression equation
t = Time.

If no degradation occurred, then β should 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 which was attributable to the time dependency. For the analysis, an r^2 value of 0.60 was used to identify possible dependencies. The main advantage of using these statistical tests was that data from intermediate tests could be utilized thereby increasing experimental confidence.

5.2 RESULTS

Table 27 summarizes the airtightness analysis using the four investigative methods described above along with the results of the first and last tests performed on each house to provide a general sense of their airtightness.

TABLE 27

SUMMARY OF AIRTIGHTNESS RESULTS

HOUSE	MONITORING PERIOD (MONTHS)	AIR BARRIER	AIRTIGHTNESS (ac/hr_{50})		EVIDENCE OF AIR BARRIER DEGRADATION? ANALYSIS METHOD			
			INITIAL	FINAL	1	2	3	4
CONVENTIONAL HOUSES								
7	36	ADA	1.17	1.42	NO	NO	NO	NO
8	36	ADA	1.59	1.11	NO	NO	NO	NO
9	36	Polyethylene	1.62	1.78	NO	NO	NO	POSSIBLE
10	36	Polyethylene	1.28	1.19	NO	NO	NO	NO
ENERGY EFFICIENT HOUSES								
1	36	ADA	1.67	1.45	NO	NO	NO	NO
2	32	ADA	1.05	1.18	NO	NO	NO	NO
3	36	ADA	1.51	1.50	NO	NO	NO	NO
4	36	ADA	1.46	1.47	NO	NO	NO	NO
5	36	ADA	1.19	1.03	NO	NO	NO	NO
6	36	ADA	1.21	1.23	POSSIBLE	POSSIBLE	POSSIBLE	NO
11	32	ADA	0.89	1.07	NO	NO	NO	POSSIBLE
12	32	ADA	1.12	1.25	NO	NO	POSSIBLE	NO
13	32	ADA	0.84	0.89	NO	NO	NO	NO
14	32	ADA	1.14	1.32	NO	NO	POSSIBLE	NO
15	32	Polyethylene	1.33	1.19	NO	NO	NO	NO
16	32	Polyethylene	1.29	1.50	NO	NO	NO	POSSIBLE
17	32	Polyethylene	0.36	0.40	NO	NO	NO	NO
18	32	Polyethylene	0.42	0.44	NO	NO	NO	NO
19	32	ADA	0.81	1.11	POSSIBLE	POSSIBLE	NO	POSSIBLE
20	32	ADA	0.71	0.87	NO	NO	POSSIBLE	NO
21	0.3	Polyethylene	1.83	1.84	--	NO	--	--
22	21	Polyethylene	0.96	1.14	NO	NO	NO	NO
23	22	Polyethylene	1.43	1.34	NO	NO	NO	NO
24	19	Polyethylene	1.39	1.29	NO	NO	NO	NO

ANALYSIS METHOD:

1. Visual examination.
2. Variation between first and last airtightness tests.
3. Variation between first and last seasonally coincident airtightness tests (see note 1).
4. Statistical tests.

NOTES:

1. Monitoring period for Analysis Method 3 may be less than total Monitoring Period, see Tables 3.

SECTION 6

ADDITIONAL MONITORING INFORMATION

6.1 MECHANICAL VENTILATION AND TOTAL AIR CHANGE RATES

Several types of ventilation systems were used in the study houses including Heat Recovery Ventilators (HRVs), integrated systems, central exhaust and point exhaust systems. Mechanical ventilation rates were estimated by monitoring the utilization of the mechanical ventilation systems, in each mode of operation (e.g. high and low speeds and defrost), and combining this data with air flow rates measured during the monthly site visits. The mechanical ventilation rates were then combined with estimates of the natural air change rate calculated using Shaw's method (1981) to arrive at predicted total air change rates. This data is included in Table 6 and shown in Fig. 45.

6.2 PRESSURIZATION CAUSED BY THE MECHANICAL VENTILATION SYSTEM

Mechanical pressurization or depressurization of the envelope occurred whenever the ventilation system operated in an unbalanced configuration. In houses with HRVs, this occurred when exhaust and supply air flow rates were unequal and whenever the units were in defrost mode (i.e. exhaust-only). The average mechanical envelope pressurization was estimated by combining the system utilization and air flow rate data with the airtightness characteristics of each house:

$$Q = C\Delta p^n \text{ or} \tag{4}$$

$$\Delta p = (Q/C)^{1/n} \tag{5}$$

where:
Q = Net unbalanced mechanical ventilation rate (l/s)
C = Flow coefficient (l/s·Pa^n)
Δp = Indoor-to-outdoor pressure differential (Pa)
n = Flow exponent (dimensionless).

Values for C and n for each house were obtained from the most recent airtightness test performed on the structure. The net unbalanced mechanical ventilation rate included the effects of supply air, exhaust air, defrost mode operation, central exhaust fan operation and make-up duct flow. Estimates of the envelope pressurization are included in Table 6 and summarized in Fig. 46.

6.3 INTERIOR CONDITIONS

Information was also collected during the monthly site visits on indoor air temperature, relative humidity and other related data, as shown in Table 6.

FIGURE 45

MEAN AIR CHANGE RATE

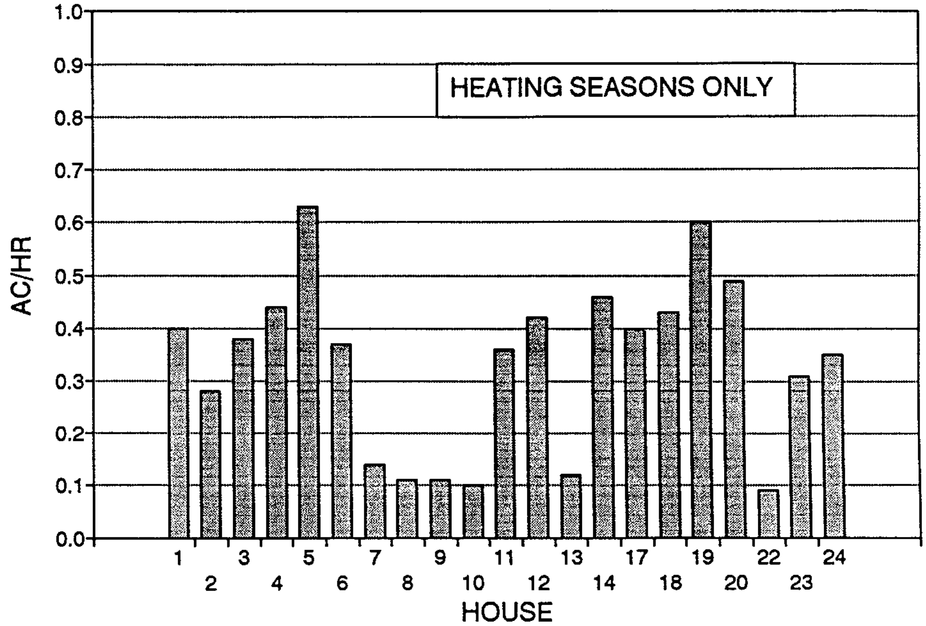
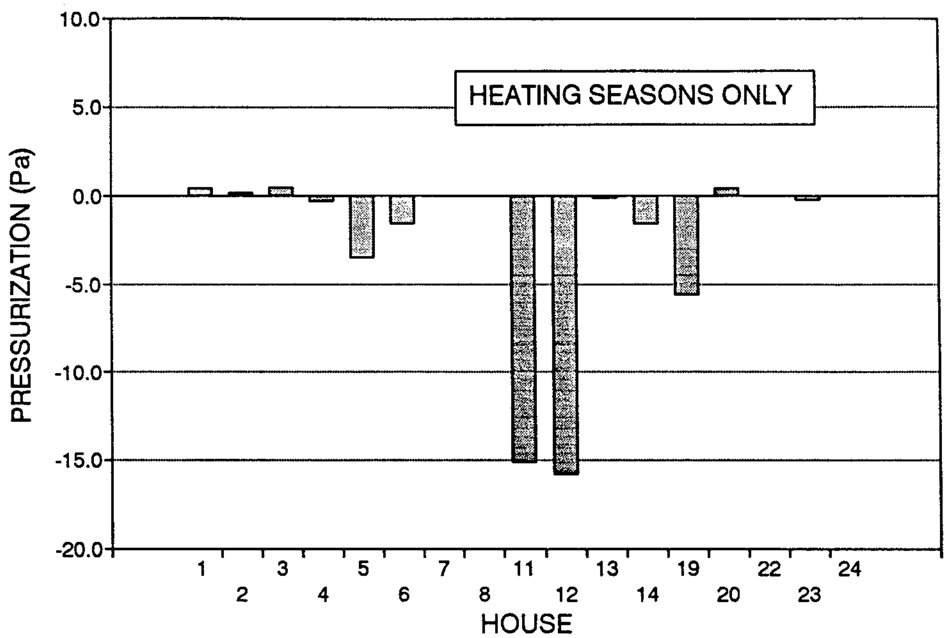


FIGURE 46

MECHANICAL PRESSURIZATION



6.4 HOMEOWNER QUESTIONNAIRES/INSPECTIONS

Questionnaires were administered to the homeowners and general inspections conducted of the houses approximately once per year. These investigated problems or faults with the building envelope such as drywall cracking, interior surface staining and damage, truss uplift, etc.

SECTION 7

PERFORMANCE OF THE CONVENTIONAL BUILDING ENVELOPE SYSTEMS

7.1 WOOD MOISTURE CONTENT

7.1.1 Walls

Table 28 summarizes the mean wall and attic WMC values, the number and percentage of readings above 19% and the number and percentage of locations which were judged as not stable below 19%. 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 (discussed in the Section 8) while WMC levels in the two conventional ADA houses (#7 and #8) were slightly higher. The largest mean wall WMC values in the study were found in Houses #7 and #8, predominately in walls with northern exposures.

The percentage of wall WMC readings exceeding 19% in the conventional houses was 3.4% (65 out of 1910 measurements), recorded at two of 16 locations in House #9, and six of 16 locations in each of Houses #7 and #8. Nine (out of 392) wall locations in the 18 project houses monitored for WMC 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 was 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 4 °C was selected as a cut-off value following a review of the literature (Baker 1969, Hoadley 1980, Mullins and McKnight 1981). The analysis showed that 46% (30 out of 65) of the wall measurements above 19% in the conventional houses occurred with a wood temperature below 4 °C. Expressed another way, the percentage of wall WMC measurements above 19% which occurred at a temperature sufficient to support fungal activity was 1.8% (i.e. 35 out of 1910).

Differences were also noted in the mean wall WMC values based on wall orientation. Using data from only the fully instrumented (i.e. four station) cavities (to insure consistent sampling locations), the mean WMC for north walls was 13.4%, vs. 10.8% for west and 9.1% for south walls.

Average predicted total air change rates during the heating season in the four conventional houses were found to be low, typically between 0.10 ac/hr and 0.14 ac/hr. 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. The Canadian Exposure Guidelines for Residential Indoor Air Quality recommends a winter relative humidity range of 30%

TABLE 28

WMC SUMMARY - CONVENTIONAL HOUSES

HOUSE	MEAN WMC (%)		MEASUREMENTS EXCEEDING 19%				LOCATIONS NOT STABLE BELOW 19%			
	WALLS	ATTICS	WALLS		ATTICS		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

to 55%, unless constrained by window condensation (HWC 1989). 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 levels. Houses #7 and #8, were operated in a largely balanced condition (since the ventilation systems were seldom run) such that pressure differentials across the envelopes were defined by natural forces (stack effect and wind action). Quantified estimates of the envelope pressure differentials were not made for Houses #9 and #10, but the houses would have been maintained in a slightly depressurized state by the naturally aspirated combustion appliances.

7.1.2 Attics

The mean WMC levels in the bottom chords of the trusses were low and generally stable, averaging 9.1%, or 2.5% lower than wall levels. Only two measurements above 19% were recorded, both in House #9. All of the monitoring locations were judged as stable below 19%.

7.2 THERMOGRAPHIC EXAMINATIONS

7.2.1 Walls and Ceilings

The mean fault count for the conventional houses was relatively constant over the monitoring period, varying from 37.0 to 35.8 (using all visible stations) and 30.5 to 34.0 (using data from only the stations continuously visible over the three year period), see Tables 22 and 23. The percentage of stations with severe faults showed a slight upward trend over the monitoring period, particularly if the data for the continuously visible stations is examined - increasing from 7.6% in 1986 to 9.0% in 1989.

The analysis of anomaly types showed that the vast majority could be categorized as either air infiltration/exfiltration, interstitial air movement or a combination of the two. Significantly, no evidence of interstitial condensation in any of the conventional houses was found during the thermographic examinations.

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 since they were also encountered in the energy efficient houses.

7.3 AIRTIGHTNESS

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

7.4 BUILDING ENVELOPE PERFORMANCE

The inclusion of the four conventional houses in the study provided a benchmark for analysis of the energy efficient structures, therefore no definitive statement on the performance of the conventional houses will be attempted. However, the observed data does highlight some of the limitations of conventional methods of constructing building envelopes.

Anomalies, in the form of elevated WMC levels, interstitial air movement and air leakage were observed with some frequency. Most of these were consistent over the monitoring period although there was little evidence to suggest general degradation of the building envelope - a point illustrated by the stability of the airtightness data. However, these faults do limit the performance of the structure by increasing energy costs, reducing comfort levels, increasing maintenance requirements and, perhaps most importantly, increasing 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, most notably the maritime provinces. Further, the houses were located in a cold, dry region. Both of these are highly desirable conditions for wood frame construction as was noted by the CMHC/CHBA Task Force on Moisture Problems in Atlantic Canada which documented the problems which may occur from using "wet" wood in humid climates (1988).

SECTION 8

PERFORMANCE OF THE ENERGY EFFICIENT BUILDING ENVELOPE SYSTEMS

8.1 WOOD MOISTURE CONTENT

8.1.1 Walls

Table 29 summarizes the mean wall and attic WMC values, the percentage of readings above 19% and the percentage of monitoring locations which were judged as not stable below 19%. Mean wall WMC levels were found to be slightly lower in the energy efficient houses compared to those in the conventional houses, 10.3% vs.11.6%. WMC levels in houses constructed with polyethylene air barriers were lower than those which 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 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 8464). Nine out of 392 wall monitoring locations in the project houses were judged as having WMC levels which were not stable below 19%. Only three of these were found in the energy efficient houses (#5, #6 and #23), even though 81% of the measurements were made in the latter group of houses.

The WMC data for the energy efficient houses was also analyzed to identify readings above 19% in which the wood temperature was too low to support the growth of wood-rotting fungi. Using 4 °C as the cut-off value, 21% (5 out of 24) of the measurements above 19% occurred at a temperature below 4 °C. Thus, the percentage of measurements exceeding 19% in the energy efficient houses at which the temperature was sufficient to support fungal activity was 0.2% (19 out of 8464), 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%. However, in the double wall houses the mean WMC was very similar for all wall orientations.

Seasonal variations in wall WMC levels differed significantly among monitoring locations. In many instances, the variation was slight with only random changes from month to month. In other cases, a pronounced seasonal effect could be observed with the maximum WMC levels occurring in the late winter and the minimum values in the late summer indicating that the wood was storing moisture in the winter and releasing it in the summer.

TABLE 29

WMC SUMMARY - ENERGY EFFICIENT HOUSES

HOUSE	MEAN WMC (%)		MEASUREMENTS EXCEEDING 19%				LOCATIONS NOT STABLE BELOW 19%			
	WALLS	ATTICS	WALLS		ATTICS		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

Six of the energy efficient houses (#11, #12, #15, #16, #19 and #20) were instrumented with WMC pins in close proximity to various construction anomalies such as electrical outlets, windows and corner framing, in anticipation of possible problems. In total, 46 sets of WMC pins were installed at these locations. Examination of the data showed that none of these had readings above 19% and none of the sites were judged as not stable below 19%.

No evidence was found of moisture entry from the outdoors into the above-grade portions of the building envelopes. Previous investigations of moisture distress has identified this as a potentially significant factor, primarily in climates with high average annual rainfall levels (Tsongas 1990). 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.

These findings are in general agreement with those reported by Sherwood in a study of condensation potential in well-insulated wall panels using an outdoor test building located in Madison, Wisconsin with controlled indoor conditions (1983). He found that the WMC of framing members did not increase significantly during a two year monitoring period.

8.1.2 Attics

Mean WMC levels in the attic trusses were slightly lower than those in the conventional houses and typically 2% to 3% lower than the wall values. Observed levels in the bottom chords were generally constant over the monitoring period. Since 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. The absence of observed moisture transport from the house interior to the attic is encouraging since this can be very destructive and result in extensive water damage to ceilings. Seasonal variations in the WMC of the top chords were more pronounced.

8.1.3 Wood Moisture Content - Floor Joists

WMC levels were consistently below 19% in House #18 for insulation/sealing Types 1 to 5 while in #20, some excursions above 19% took place on the west wall with Types 2, 3, 4 and 5. No satisfactory explanation was found to explain these high levels, although it was noted they tended to occur at the same time of year (June). Both houses were operated with the mechanical ventilation system providing a slight degree of positive pressurization. However, these excursions are not considered representative of any endemic problem with either the basement insulation system used on #20 or the air/vapour barrier systems studied.

The concerns regarding floor joist insulation/sealing systems were developed with respect to retrofits of existing structures - which have some fundamental differences with modern construction practices. The most obvious of these are the practices of applying a dampproofing membrane to the exterior concrete wall and the use of aggregate or polyethylene under the floor slab. Both of these measures are intended to provide a break to control capillary flow of water into the foundation. In most cases, the only contact between the concrete and soil is the at the bottom of the footings.

In some situations, moisture transport from the soil to the basement wall may also be impeded by the existence of shrinkage cracks between the soil and the wall. These may develop in some soil types during dry periods and may reach a considerable depth below grade.

While these results do not provide a definitive statement on the performance of cast-in-place floor systems with interior insulation, the absence of high WMC levels, particularly in House #18, is encouraging. Based on these observations, it was concluded that there was not sufficient evidence to indicate that high levels of interior insulation will create wood decay problems in houses which use cast-in-place floor joist systems provided dampproofing layers or membranes are used on the outside of the basement wall and underneath the floor slab.

8.2 THERMOGRAPHIC EXAMINATIONS

8.2.1 Walls and Ceilings

The thermographic data shows that the performance of the energy efficient building envelopes was consistent 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 declined in a similar fashion. 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 the conventional houses, as indicated by both the mean fault count and the percentage of stations with severe faults.

The thermographic data also showed that ceiling anomalies were less frequent and of reduced magnitude in houses which used continuous polyethylene air barriers on the ceiling installed prior to the partition walls (#15 to #18).

The type analysis found that the vast majority of anomalies could be 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). Significantly, 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 #21) and, in the case of Houses #11 to #20, was not installed until after the first thermographic examinations and airtightness tests had been performed. The separate study of airtightness in the project houses has already shown that stucco can produce a significant reduction in air leakage rates with most types of construction. Examination of the thermographic data shows that there was a reduced incidence of anomalies along the floor line in some of the ADA houses (notably #11, #12 and #20) after the stucco had been installed, possibly indicating a reduction in air leakage in this region.

8.2.2 Problem Details

Several types of construction details were found to consistently produce thermographic anomalies in both the energy efficient and conventional houses:

a) Bow window framing - Primarily installed in bedrooms but also in some living rooms, bow windows were major sites for significant amounts of interstitial air movement. The windows were installed in walls constructed using standard 38x140 (2x6) framing or framing with exterior insulated sheathing. In many instances, the thermal images suggested an interaction, in the form of interstitial air movement, between the main wall and the window framing. In many of the ADA houses, the anomalies were particularly strong 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. In the majority of cases, this wall displayed a massive thermal anomaly over most or all of its surface which was subsequently categorized as interstitial air movement. The anomaly was also evident on some intersecting partition walls. The exact cause could not be determined but one possibility is that the cavity insulation in the wall detached itself from the drywall surface due to an absence of exterior sheathing on the cold (attic) side thereby permitting air movement between the insulation and the drywall.

c) Plumbing walls - Plumbing walls were constructed between kitchens and bathrooms using 38x140 (2x6) framing. In many instances, particularly in the ADA houses, significant interstitial air movement was observed on one or both sides of the wall during the thermographic examinations, 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. Another possibility is that the presence of the 100 mm (4") plumbing stack created a thermal weak spot permitting air flow/leakage down the stack.

d) Exterior doors/entrance ways - Interstitial air movement was frequently noted in the exterior wall in the vicinity of the entrance door. Anomalies were also noted near the short divider walls, which intersected the exterior wall near the entrance door (used to provide a spatial separation for the entrance). Faults were observed with all wall construction types, including the double walls, though to varying degrees and intensities.

Since these anomalies were found in many, and in some cases, most houses they can not be attributed to faulty workmanship or poor materials. They represent in most cases, systematic faults which can be expected to occur whenever such details are used. However, their significance is difficult to assess. Merchant-built housing can not be expected to provide a fault-free envelope particularly when evaluated using an examination tool with the sensitivity of thermography (for example, the temperature difference between full white and full black on most of the thermograms was only 2 °C).

Thus, what is the significance of these systematic anomalies? In the short term, i.e. over the three year monitoring period of this study, the answer is probably: minimal. The anomalies did not result in service requests or warranty claims, their impact was not evident using normal human senses and they were not apparent to the homeowners. Nonetheless, it would be desirable to investigate them in more detail - both to better understand their cause and to develop construction details which might minimize or eliminate their occurrence. Improved details would not only help to insure the long-term integrity of the envelopes but might reduce major problems in housing exposed to more hostile environments (e.g. maritime and northern climates) or severe operating conditions (e.g. high occupancy loads, humidity levels, etc.).

Therefore, it is recommended that a laboratory and field testing program be established to systematically investigate the performance of all building envelope components when constructed using alternative techniques. Infra-red thermography, component air leakage testing and wood moisture content analysis should be included. This study should also include a cost assessment of the various alternatives to optimize the recommendations.

8.3 AIRTIGHTNESS

The four airtightness analysis methods which were used to evaluate the 20 energy efficient structures identified 11 occurrences of possible, albeit slight, evidence of airtightness degradation in two of the ten polyethylene houses and six of the 14 ADA houses. However, the magnitude of these changes was small and they were not judged to be of practical significance. The airtightness study concluded that no definitive evidence was found of air barrier degradation in the energy efficient houses (Proskiw 1992). The study also concluded that no evidence was found to indicate that either the polyethylene or ADA systems were unsuited for use in residential construction.

8.4 HOMEOWNER QUESTIONNAIRES/INSPECTIONS

The questionnaires and house inspections generally revealed only minor building envelope problems. Drywall cracking, which may have a significant impact on the performance of ADA houses, was reported in virtually all houses, particularly along corner beads and frequently under windows and near doorways, although its impact upon airtightness was not detectable. Paint problems were also noted in many houses, specifically with poor adhesion of the paint, permitting it to be easily rubbed off. Truss uplift was also noted in a few houses. Ceiling staining problems caused by melting of snow which had blown into the attic during a blizzard was reported in one ADA house.

A problem detail which was identified during the house inspections concerned the interior surface of the exterior bathroom wall. This was found in at least six houses (four of them ADA). Houses #1 to #20 were constructed using conventional drywall as the wall surface in the bathrooms, including the bathtub/shower area. The drywall was primed and, in some cases, painted and then covered with ceramic tile. In the cases described, the tile grout failed resulting in destruction of the adhesive which lead to tile bulging and separation. In the ADA houses, this left the wall particularly vulnerable to water damage. One of these houses, #6, was equipped with two WMC monitoring pins in a stud on the bathroom wall. WMC levels were checked and found to be normal (no measurements above 19% were recorded). In houses constructed with polyethylene air barriers, moisture transport into the walls would have been limited by the polyethylene, although the drywall was damaged. (This bathroom drywall detail was subsequently changed on Houses #21 to #24 to require a waterproof material in place of conventional drywall around the bathtub/shower area.)

8.5 PRESSURIZATION CAUSED BY THE MECHANICAL VENTILATION SYSTEM

Mechanical ventilation flow rates were adjusted approximately once per year to balance or slightly unbalance the supply and exhaust flows. However, the calculated pressurization was frequently found to be significantly different from that expected. For example, several houses intended to function in a balanced configuration actually operated in an unbalanced state because of equipment problems (burned out blowers, malfunctioning controls, etc.), poor balancing or homeowner intervention. Although the wide variations in pressurization in the project houses makes it difficult to draw firm conclusions, some interesting observations can be made.

The combination of powerful ventilation systems and airtight building envelopes permitted significant levels of mechanically-induced pressurization/ depressurization to be created in several of the energy efficient houses. This did not occur in the conventional houses because the ventilation systems were seldom used and, in some cases, did not have sufficient flow capacity to create a significant level of depressurization. Houses #11 and #12 were designed to function in an unbalanced configuration and their mean pressurization levels were -15.1 Pa and -15.8 Pa, respectively (the negative sign indicating depressurization). The extreme monthly value was estimated to be -28.8 Pa, which occurred in House #12.

Examples of other extreme monthly values included House #1 (5.1 Pa) and #5 (8.6 Pa and -13.9 Pa). Positive pressurization is a concern because it may increase moisture deposition in the envelope as the result of air exfiltration. For example, CAN/CSA-F326-M91 "Residential Mechanical Ventilation Systems" specifies a maximum positive pressurization of 10 Pa which can be induced by the ventilation system (1991), although the justification for this figure is based on limited knowledge.

8.6 BUILDING ENVELOPE PERFORMANCE

8.6.1 Performance of Energy Efficient vs. Conventional Building Envelope Systems

The building envelopes in the energy efficient houses were judged to have performed in a superior fashion to those in the houses with conventional envelopes. Mean wall and attic WMC levels were lower and more stable, fewer instances were found of WMC levels exceeding 19% and a smaller percentage of monitoring locations were judged as not being stable below 19%, see Figs. 36 to 39. The energy efficient houses also demonstrated a lower incidence of thermographic anomalies, particularly those of a severe nature. No evidence was found during the thermographic examinations to suggest that any of the project houses experienced interstitial condensation in their envelopes. Airtightness testing showed that leakage rates were lower in the energy efficient houses, especially those using the double wall system.

8.6.2 Degradation of Energy Efficient Building Envelopes

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

8.6.3 Evidence of Elevated Moisture Levels in the Energy Efficient House Envelopes

Based on the WMC measurements and thermographic examinations, 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, attics and floor joist/header areas were not observed to demonstrate an unusual incidence of problems. Also, those houses constructed with sandwiched air/vapour polyethylene barriers (double walls and walls with interior insulated strapping) did not display elevated WMC levels or any evidence of interstitial condensation.

8.6.4 Polyethylene Air Barriers vs. the Airtight Drywall Approach

Building envelopes constructed using polyethylene air barriers generally performed in a superior fashion to those built using the ADA system, although both functioned in a satisfactory manner. WMC levels were slightly lower in the polyethylene houses, and the mean thermographic fault counts and the percentage of monitoring stations with severe faults were also lower in the polyethylene houses, see Figs. 40 to 43. Both types of construction demonstrated stable airtightness rates.

The success of the polyethylene houses was also partially attributable to the number of double wall houses in the study. It should also be recognized that most of the ADA houses were constructed using early versions of the system. Since their design, many changes - specifically in the types of materials used for gaskets - have improved the durability and performance of the ADA system.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 PERFORMANCE OF ENERGY EFFICIENT vs. CONVENTIONAL BUILDING ENVELOPE SYSTEMS

- The performance of the building envelopes in the energy efficient houses was judged to have been superior to that observed with the conventional envelope systems. Lower mean wood moisture content levels were measured in the walls and attics and fewer WMC 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. Airtightness testing showed that the leakage rates were lower in the energy efficient houses.

9.2 DEGRADATION OF ENERGY EFFICIENT BUILDING ENVELOPES

- No evidence of envelope degradation was found in any of the energy efficient houses. Both the polyethylene air barrier and ADA houses demonstrated predominately stable WMC levels, thermographic characteristics and airtightness rates over the three year monitoring period.

9.3 EVIDENCE OF ELEVATED MOISTURE LEVELS IN THE ENERGY EFFICIENT HOUSE ENVELOPES

- 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, attics and floor joist/header areas did not display an unusual incidence of problems, elevated WMC levels or evidence of interstitial condensation. This included a group of houses which were constructed with sandwiched polyethylene air/vapour barriers (double walls and frame walls with interior strapping). These results were also interpreted as a demonstration of the benefits of using dry wood and a low leakage air barrier (to minimize moisture transport into the envelope).

9.4 POLYETHYLENE AIR BARRIERS vs. THE AIRTIGHT DRYWALL APPROACH

- The building envelopes constructed using polyethylene air barriers generally performed in a superior fashion to those which used the ADA system, although both were judged as satisfactory. WMC levels were slightly lower in the polyethylene houses while the mean thermographic fault counts and the percentage of monitoring stations with severe faults were lower in the polyethylene houses.

9.5 PROBLEM DETAILS

- o Several types of construction details were found to consistently produce thermographic anomalies in both the energy efficient and conventional houses. The most significant were: a) the wall framing around bow windows (particularly in ADA construction at the wall/floor interface), 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) the wall framing around exterior doors/entrance ways. Possible explanations were suggested for each anomaly.

9.6 RECOMMENDATIONS

- o A laboratory and field testing program should be established to systematically investigate the performance of major envelope components, each constructed with various alternative details. Infra-red thermography, component air leakage testing and wood moisture content analysis should be included along with a cost analysis of the various options.

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APPENDIX A

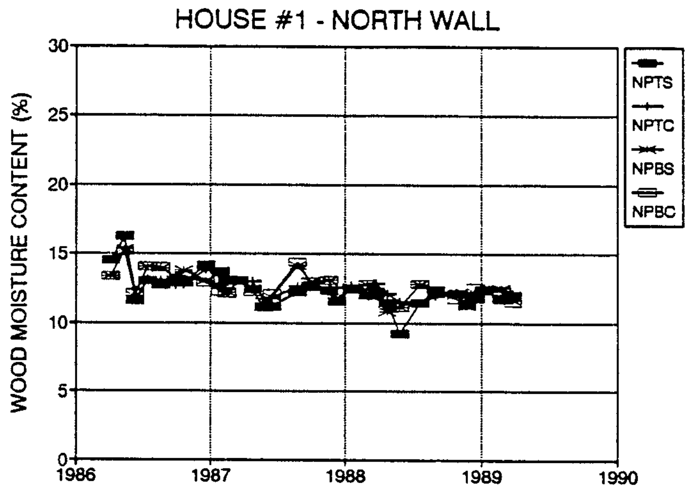
WMC PROBE NOMENCLATURE:

4 characters; e.g.: N--Wall direction (North, East, South, West)
P--Plate (top or bottom) or Stud
T--Top or Bottom of cavity or Warm or Cold side of stud
S--Shell or Core of member

3 characters beginning with "A"; e.g.:
A--Attic
B--Bottom chord or Top chord
S--Shell or Core of member

3 characters beginning with "E" or "W", Houses #18 and #20 only; e.g.:
E--Wall direction (East or West)
A--Position on floor joist (A,B,C, or D)
1--Floor joist header insulation/sealing method (1,2,3,4,5)

3 characters beginning with "E" or "W", House #23 only, denotes horizontal strapping; e.g.: N--Wall direction (North, East or West)
T--Height of strapping (Top, Mid-Height or Bottom of wall)
S--Shell or Core of member


HOUSE #1 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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20
15
10
5
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1986
1987
1988
1989
1990
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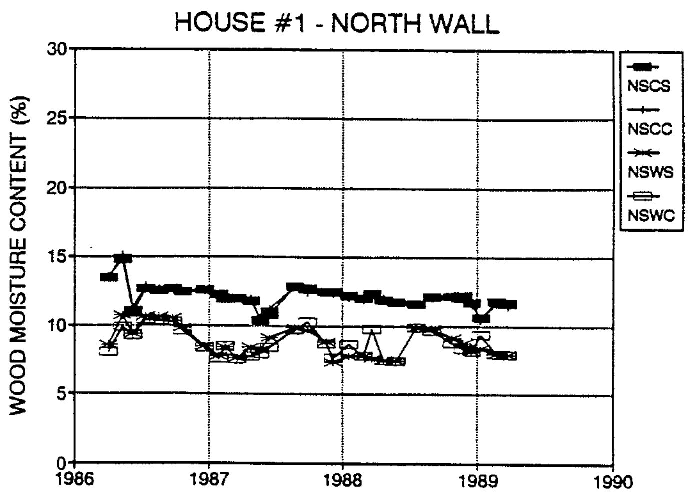
NPTC
NPBS
NPBC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1989
1990
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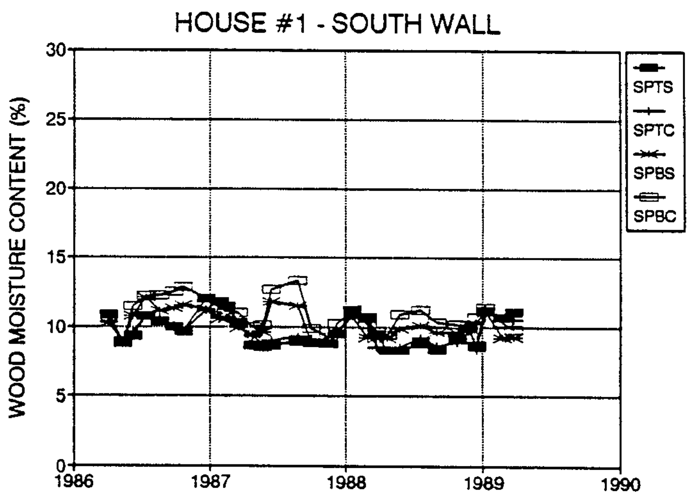
NSCC
NSWS
NSWC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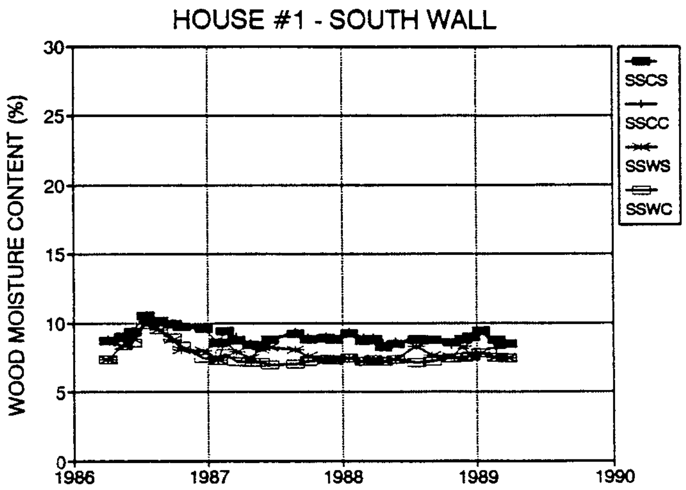
SPTC
SPBS
SPBC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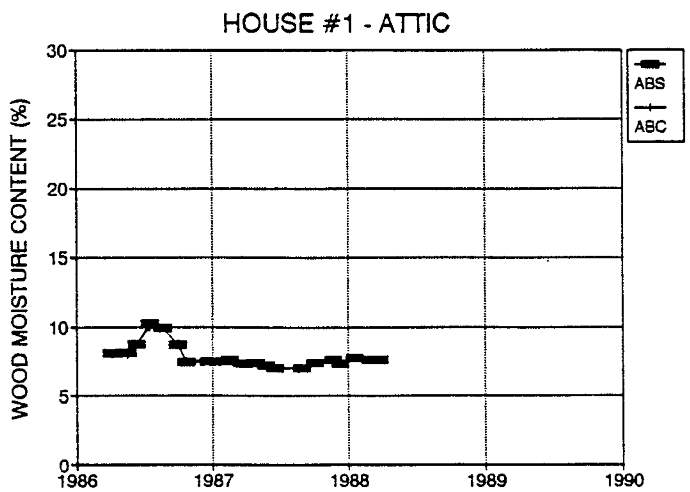
SSWS
SSWC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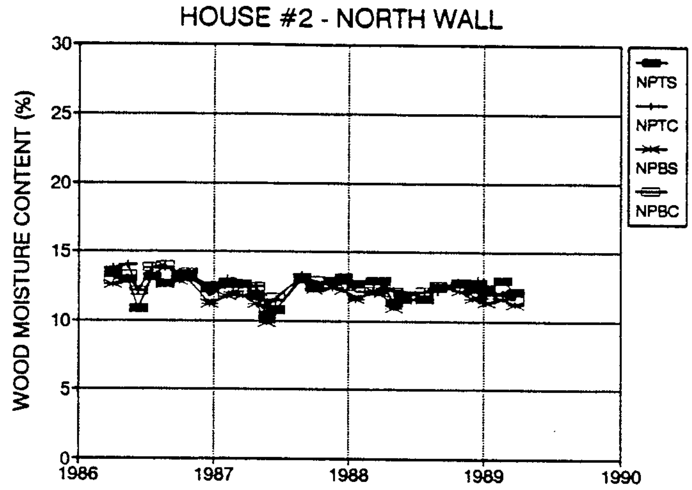
ABC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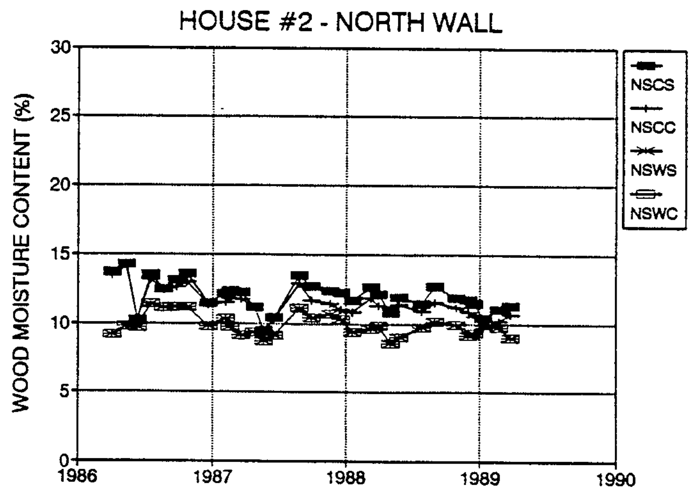
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NSWS
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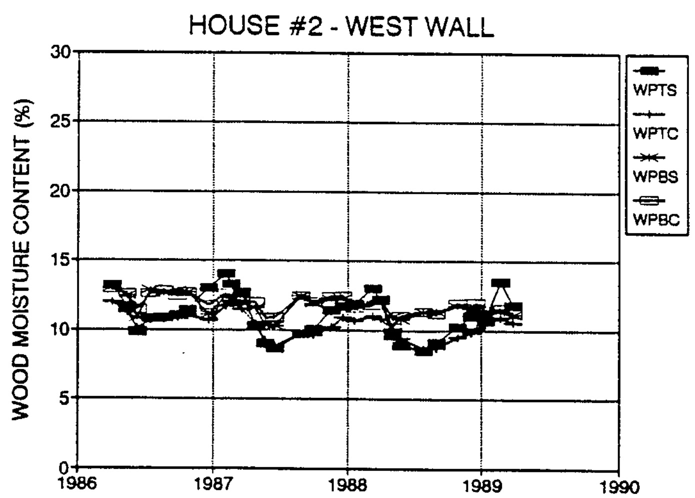
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WOOD MOISTURE CONTENT (%)
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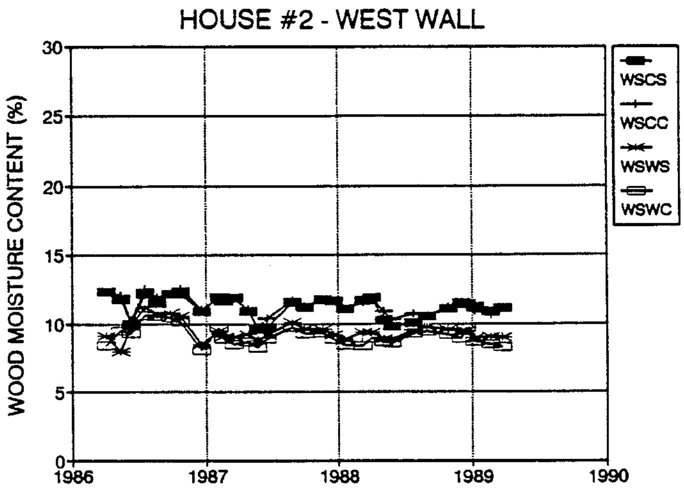
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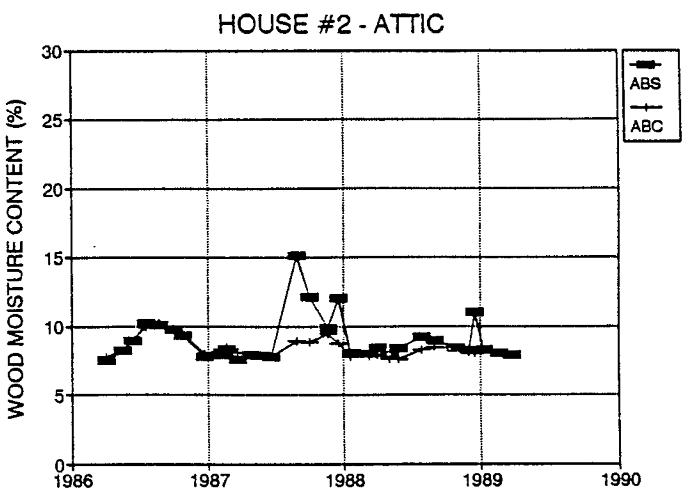
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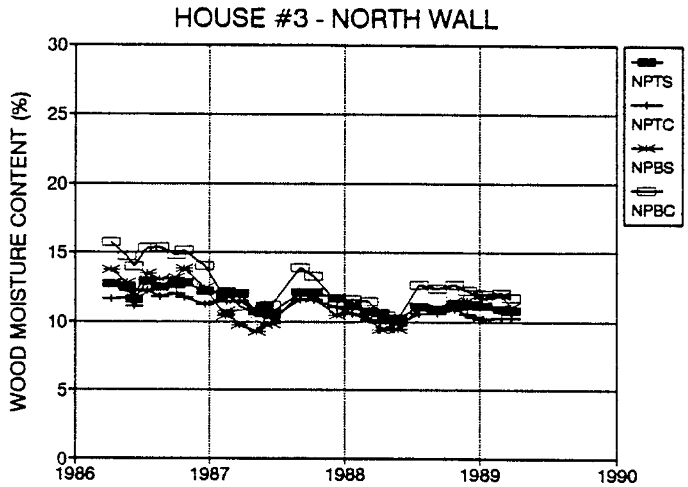

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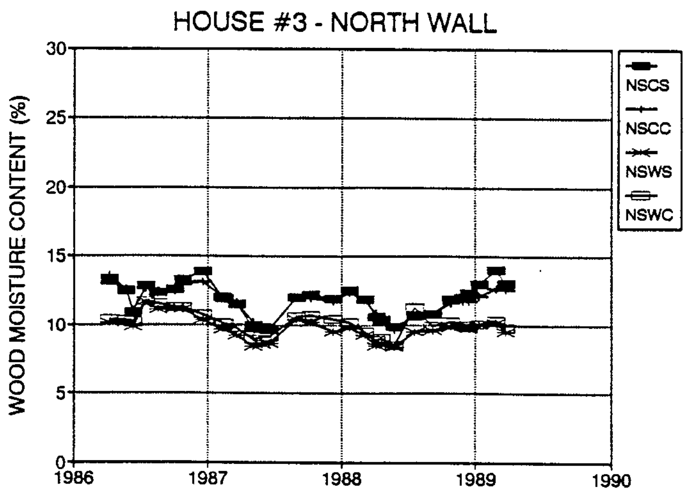

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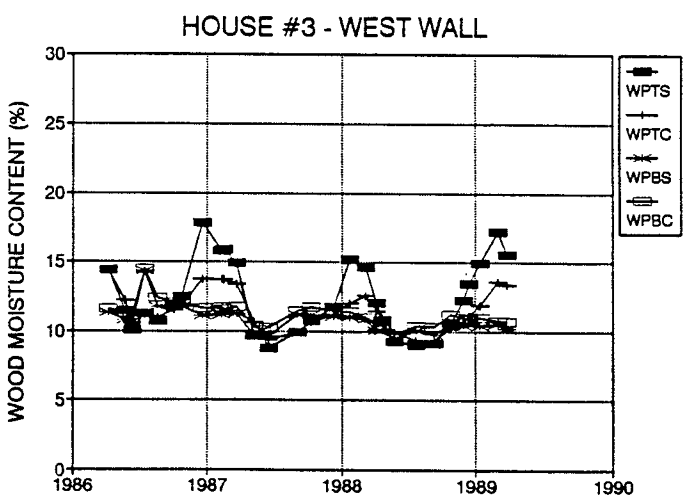

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WOOD MOISTURE CONTENT (%)
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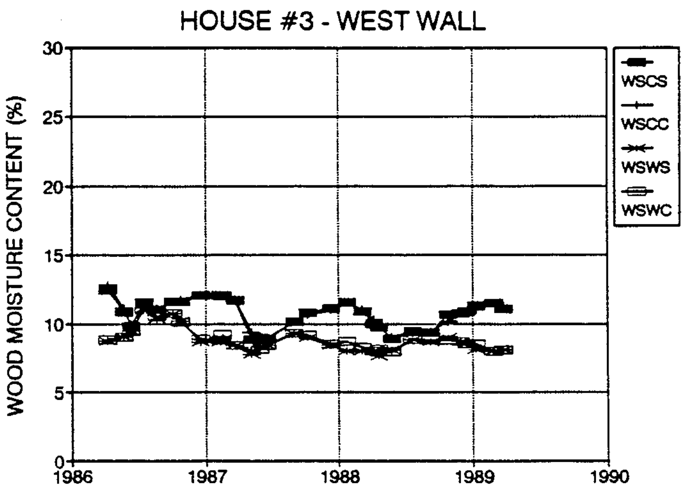

HOUSE #3 - WEST WALL
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WSWS
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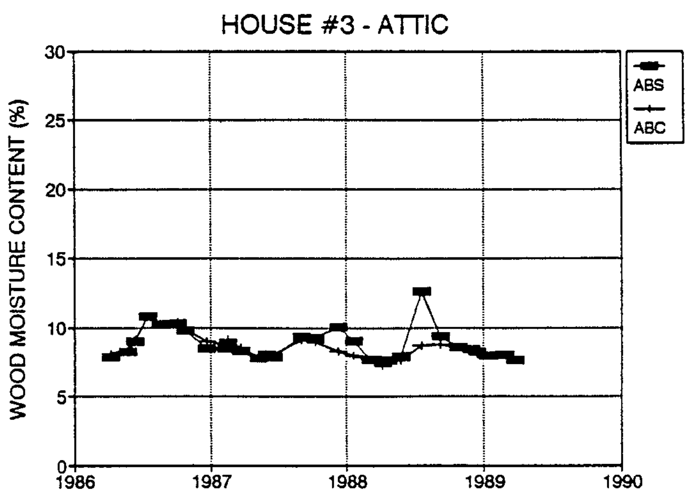

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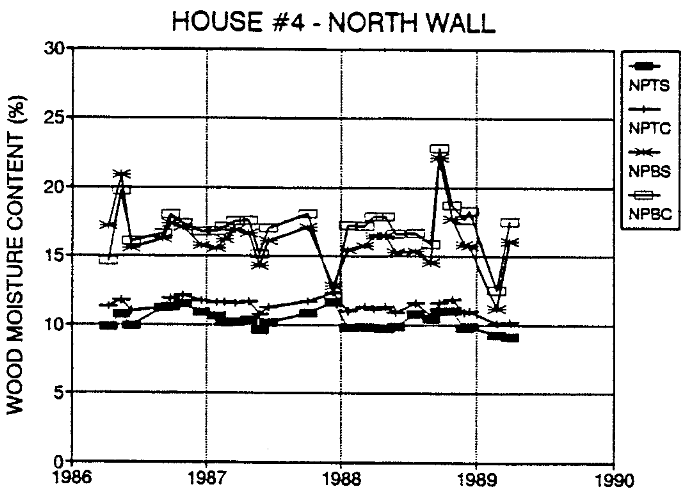
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WOOD MOISTURE CONTENT (%)
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NPBS
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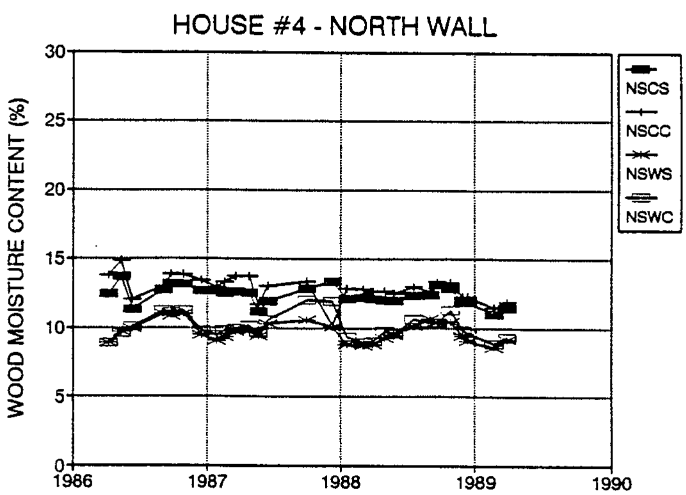
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NSWS
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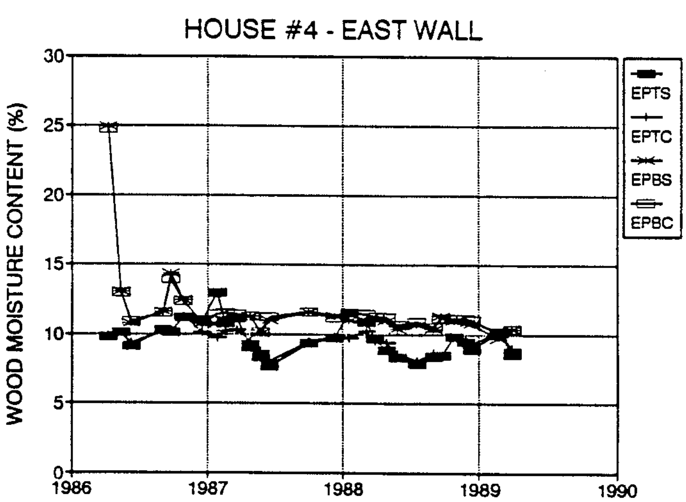
HOUSE #4 - EAST WALL
WOOD MOISTURE CONTENT (%)
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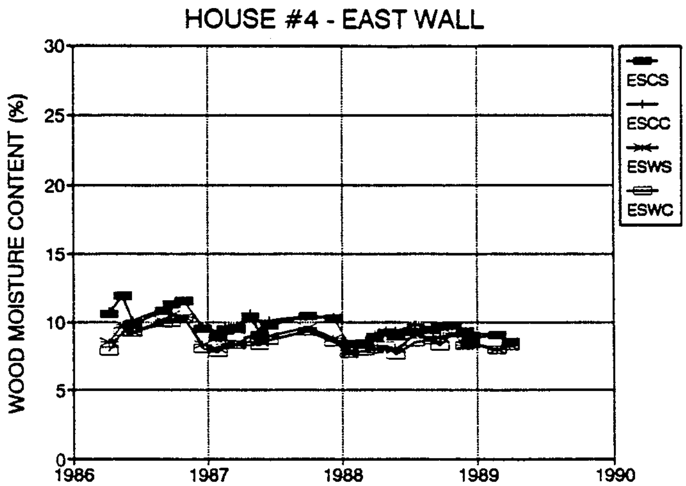
EPTC
EPBS
EPBC


HOUSE #4 - EAST WALL
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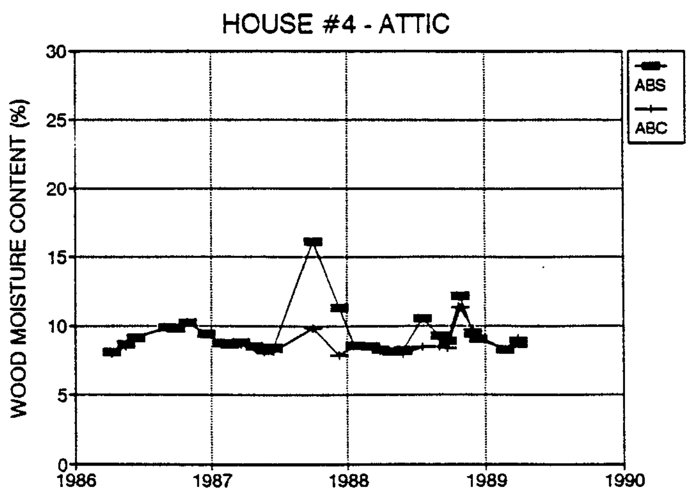
ESWS
ESWC


HOUSE #4 - ATTIC
WOOD MOISTURE CONTENT (%)
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1989
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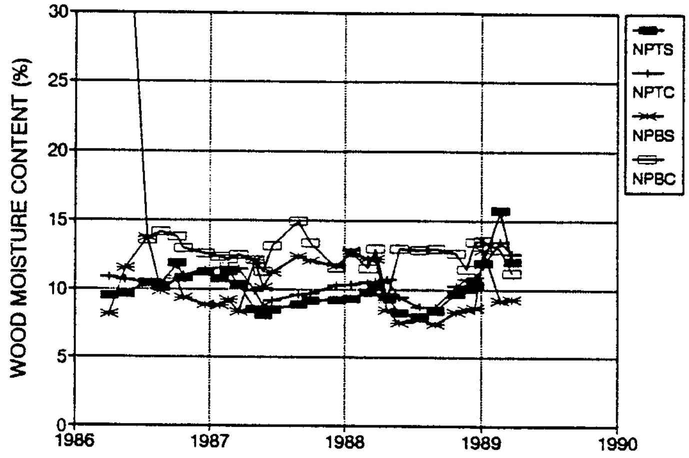
ABC

HOUSE #5 - NORTH WALL



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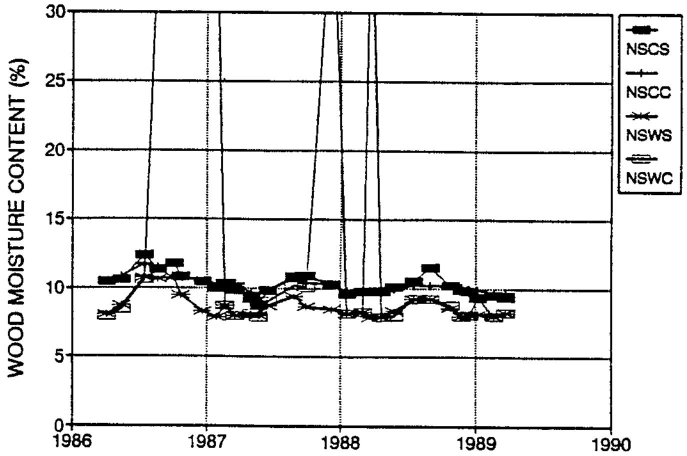

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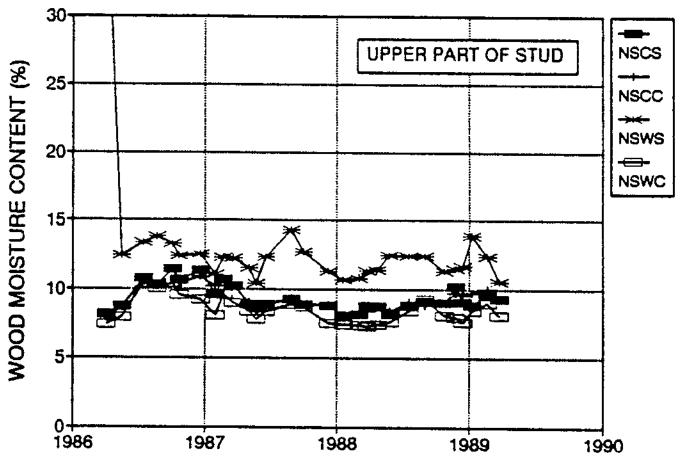

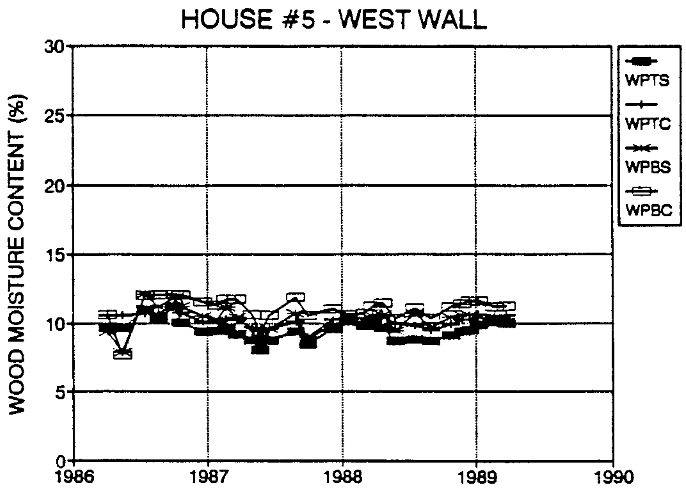
HOUSE #5 - WEST WALL
WOOD MOISTURE CONTENT (%)
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WPBS
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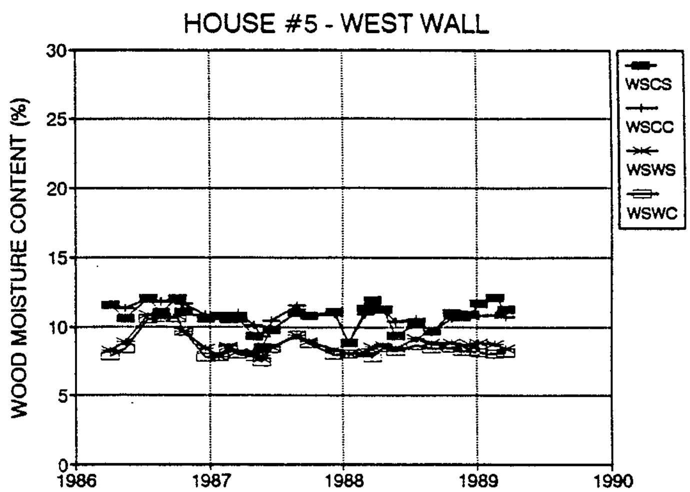
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WOOD MOISTURE CONTENT (%)
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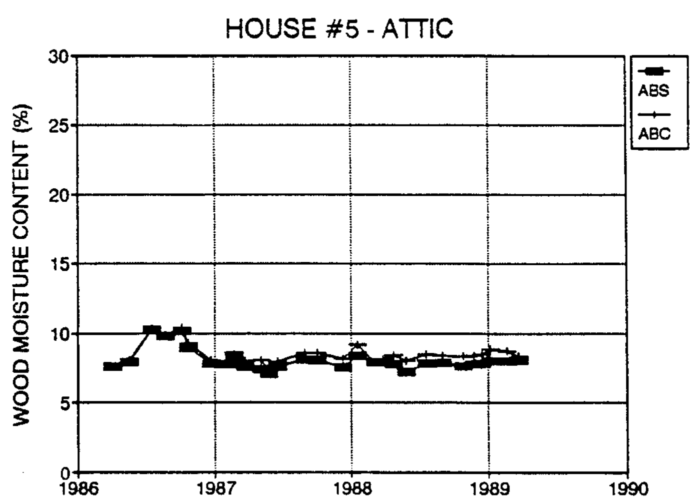
WSWS
WSWC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20
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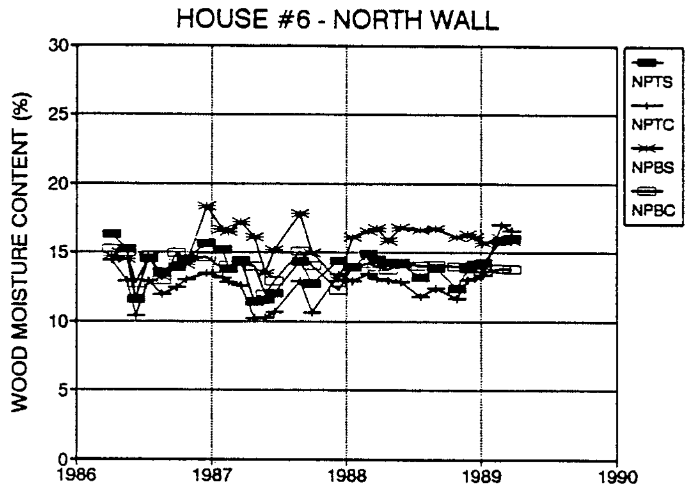
1988
1989
1990
ABS
ABC


HOUSE #6 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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15
10
5
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1987
1988
1989
1990
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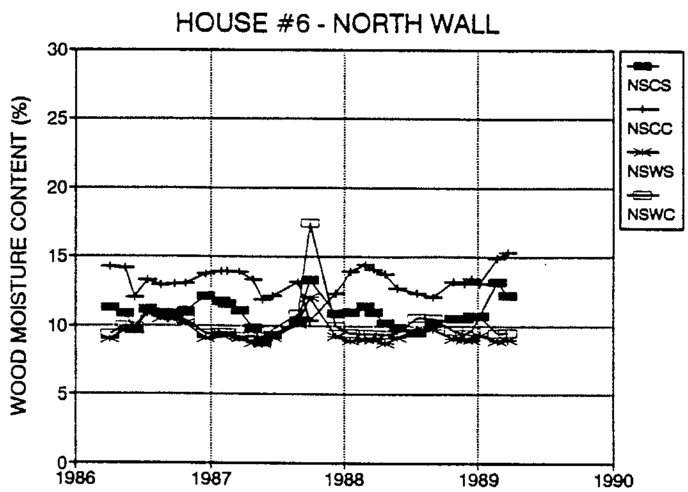
NPTC
NPBS
NPBC


HOUSE #6 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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1987
1988
1989
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NSCS
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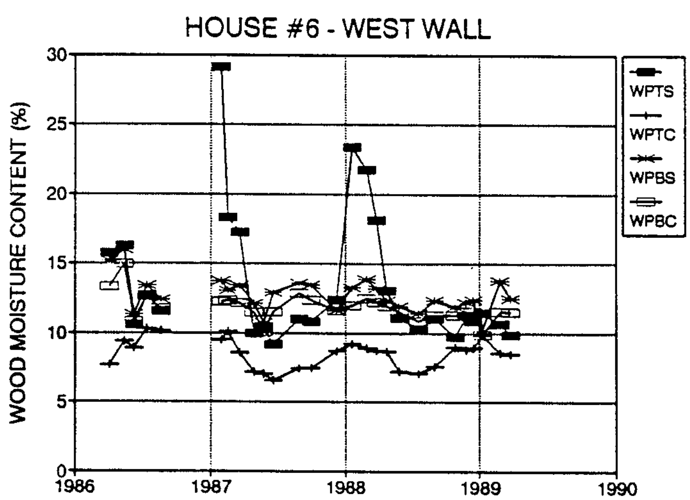
NSWS
NSWC


HOUSE #6 - WEST WALL
WOOD MOISTURE CONTENT (%)
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15
10
5
0
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1989
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WPTC
WPBS
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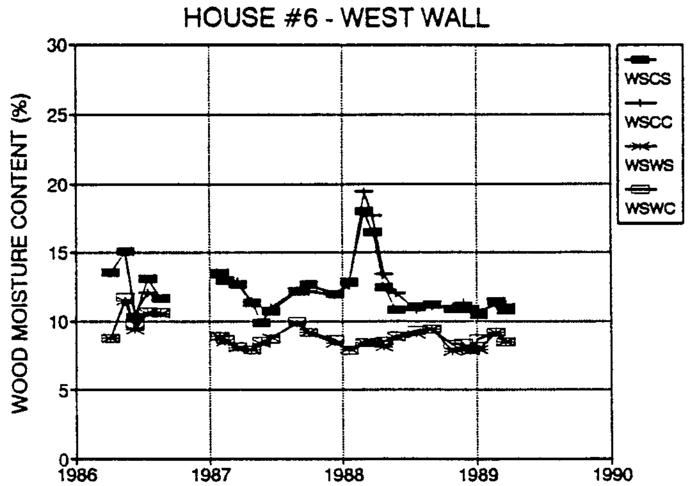
HOUSE #6 - WEST WALL
WOOD MOISTURE CONTENT (%)
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WSCC
WSWS
WSWC
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25
20
15
10
5
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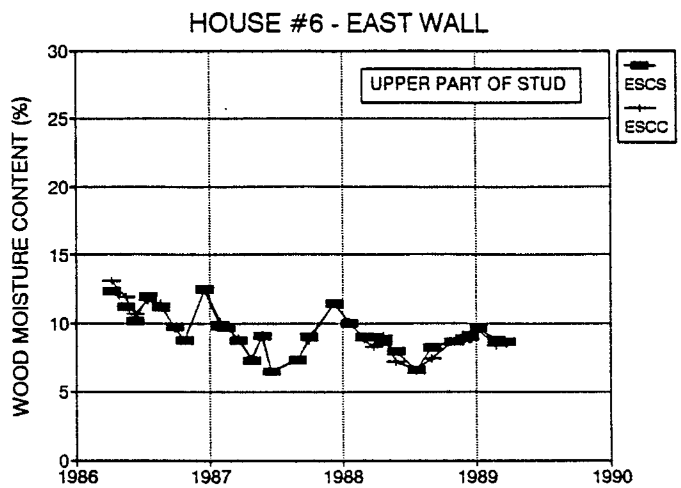
1986
1987
1988
1989
1990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UPPER PART OF STUD
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ESCC
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25
20
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10
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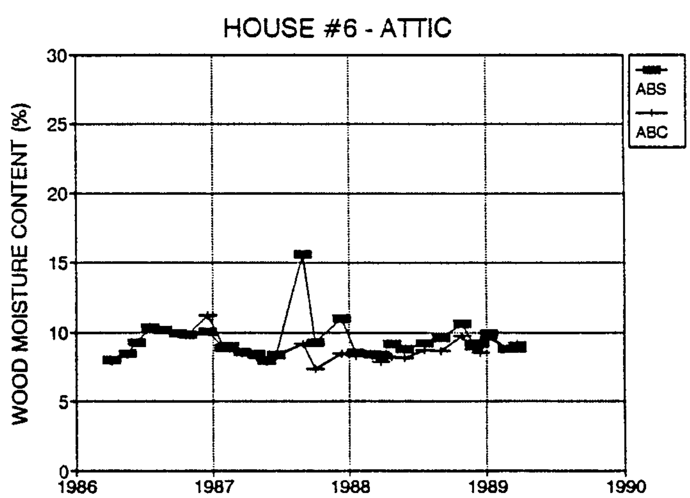
1986
1987
1988
1989
1990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ABC
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1987
1988
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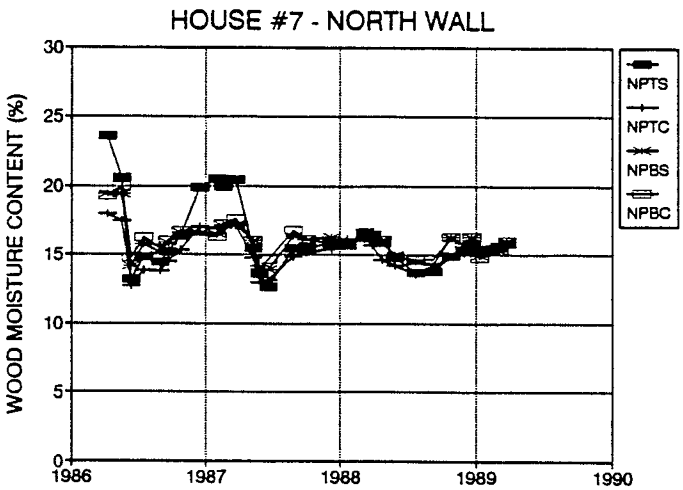
1990


HOUSE #7 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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NPTC
NPBS
NPBC
0
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10
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20
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30
1986
1987
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1989
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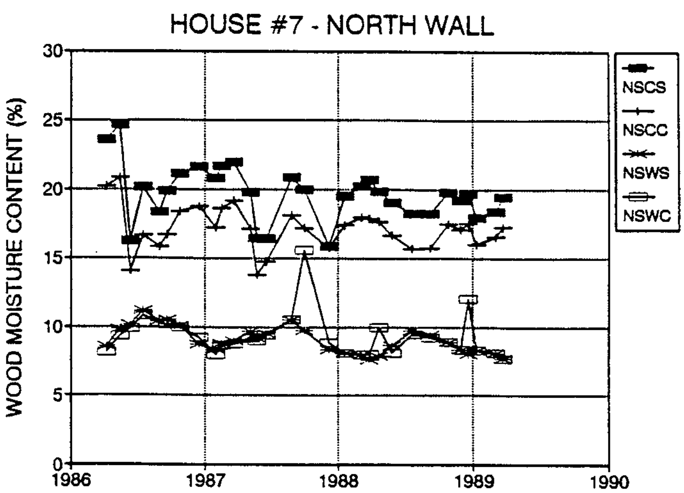
HOUSE #7 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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NSWS
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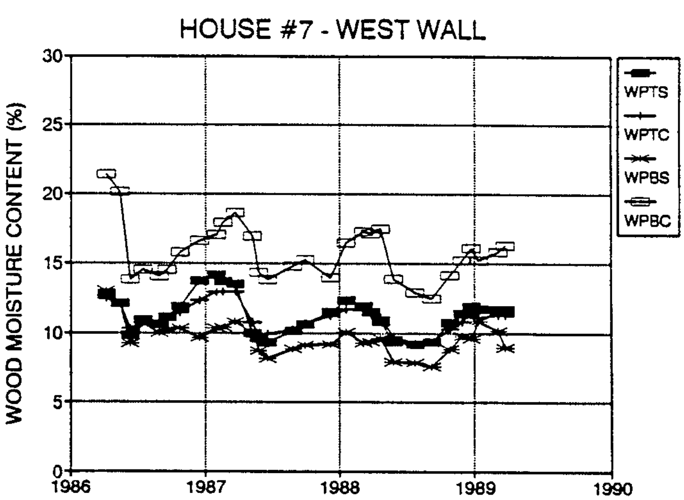
1986
1987
1988
1989
1990


HOUSE #7 - WEST WALL
WOOD MOISTURE CONTENT (%)
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WPTC
WPBS
WPBC
0
5
10
15
20
25
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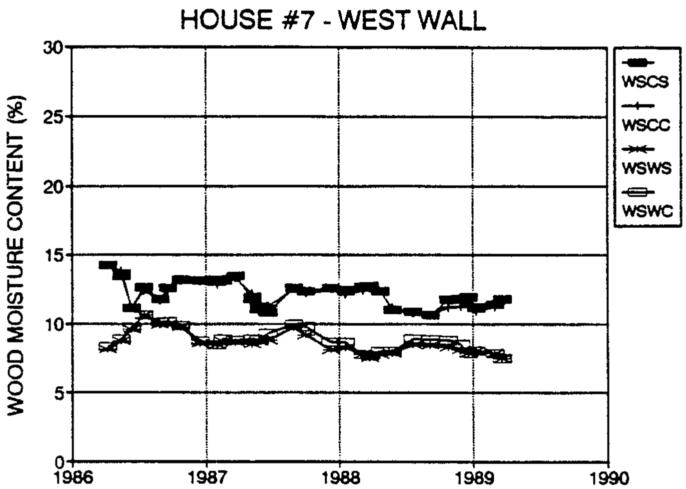
1986
1987
1988
1989
1990



HOUSE #7 - WEST WALL
WOOD MOISTURE CONTENT (%)
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20
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10
5
0
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1987
1988
1989
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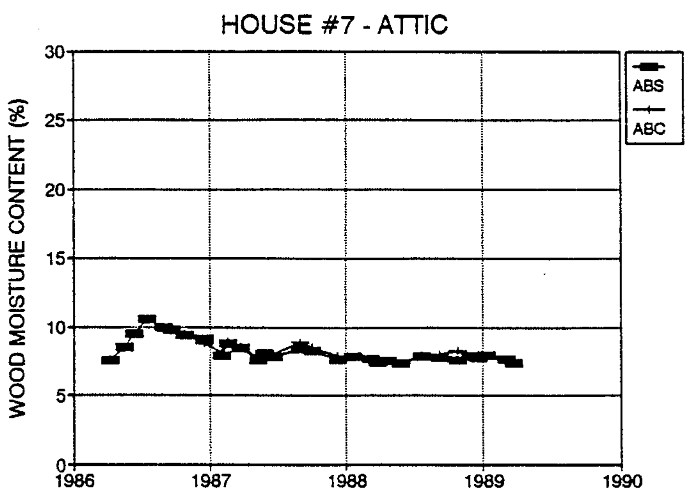
WSCS
WSCC
WSWS
WSWC



HOUSE #7 - ATTIC
WOOD MOISTURE CONTENT (%)
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25
20
15
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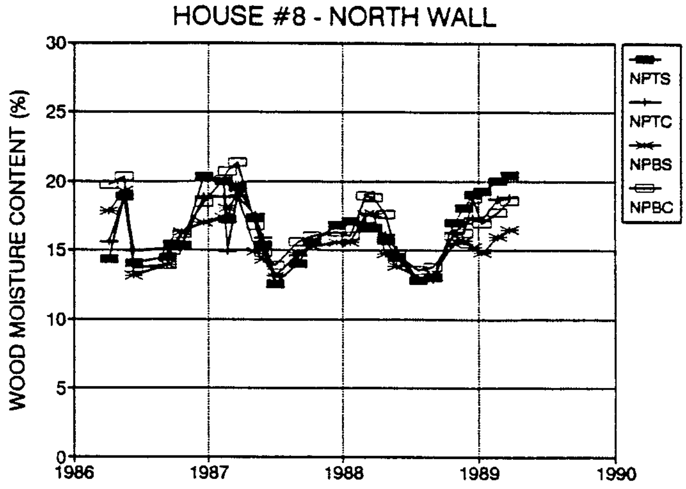
1986
1987
1988
1989
1990
ABS
ABC


HOUSE #8 - NORTH WALL
WOOD MOISTURE CONTENT (%)
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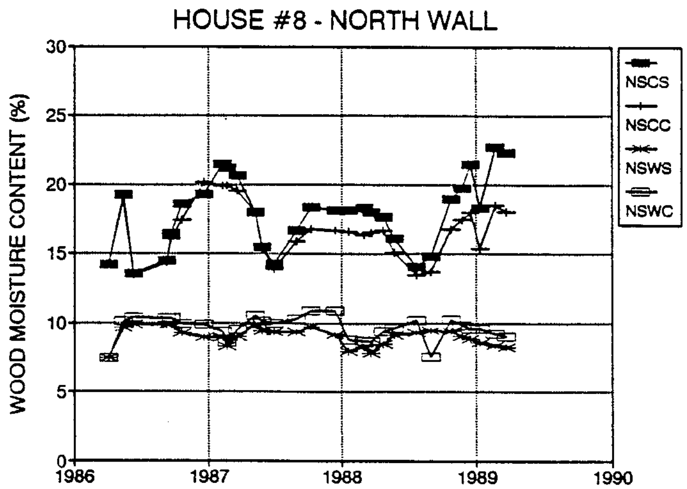
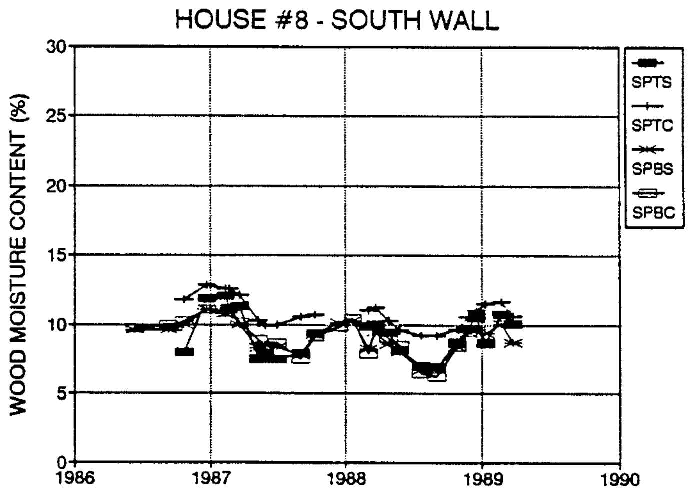
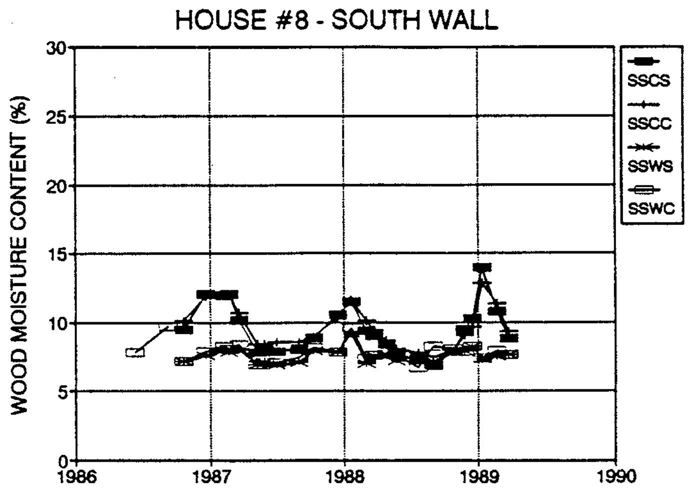
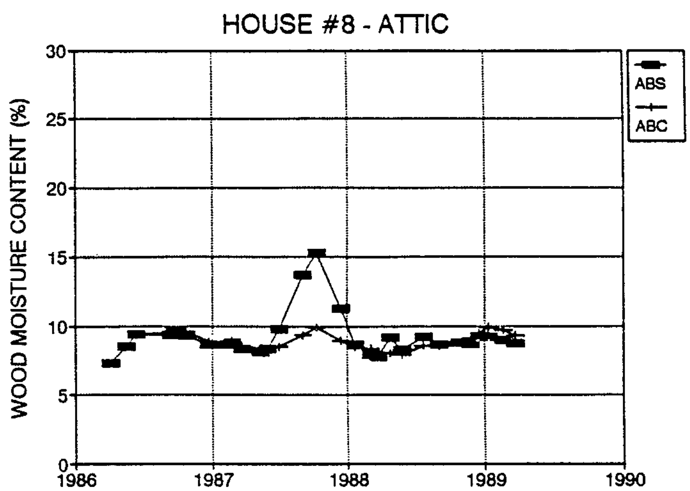
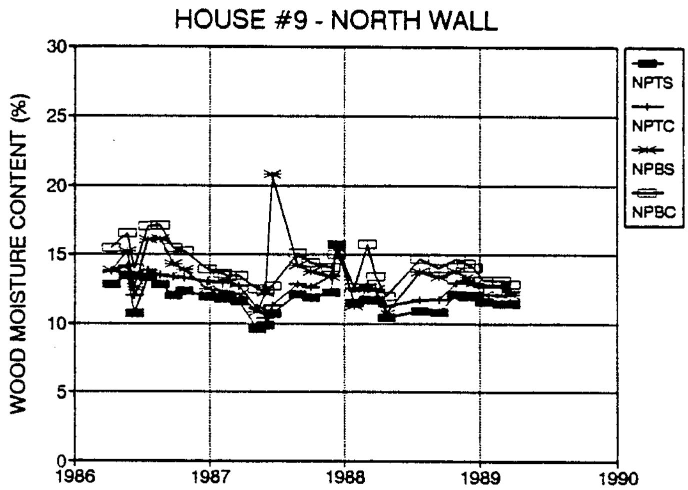
5
10
15
20
25
30
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

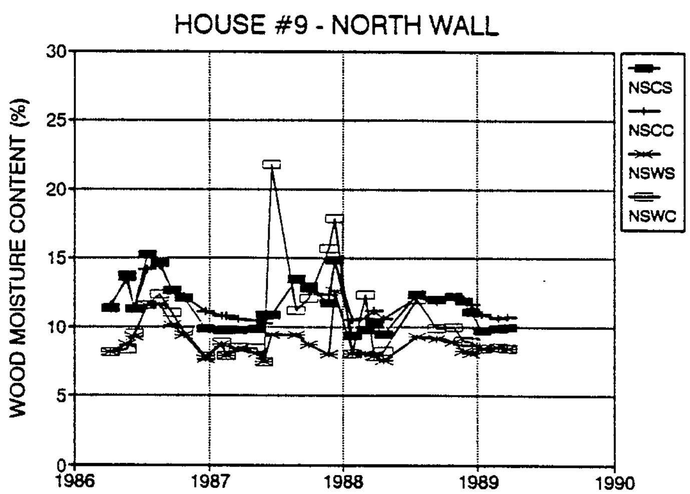

HOUSE #8 - NORTH WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

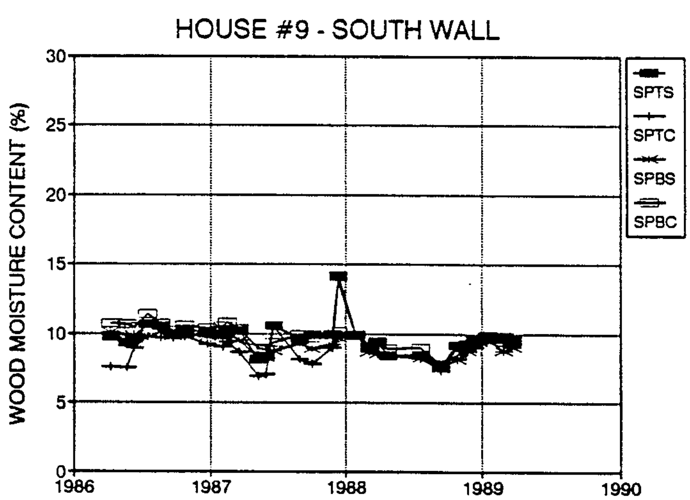

HOUSE #8 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
SPTS
SPTC
SPBS
SPBC

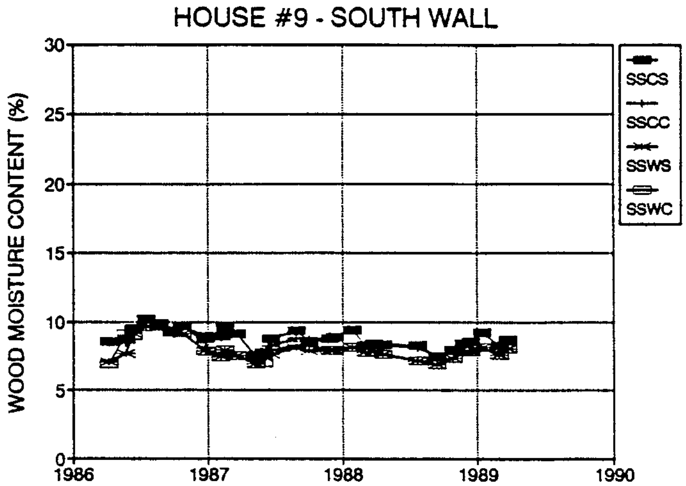

HOUSE #8 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SSCS
SSCC
SSWS
SSWC


HOUSE #8 - ATTIC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ABS
ABC


HOUSE #9 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC


HOUSE #9 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC


HOUSE #9 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SPTS
SPTC
SPBS
SPBC


HOUSE #9 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
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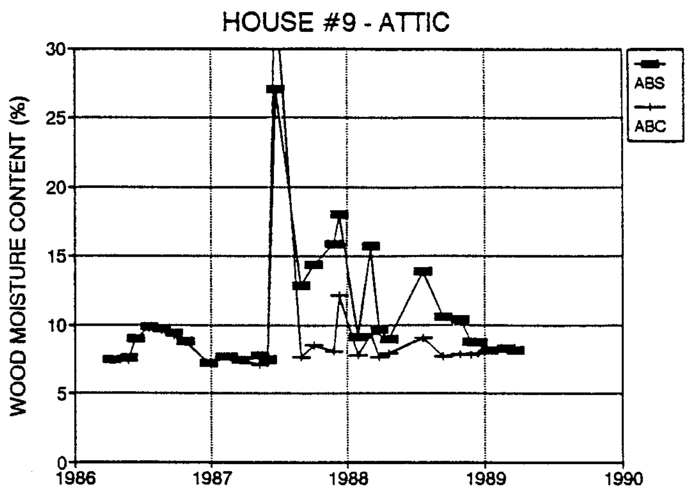
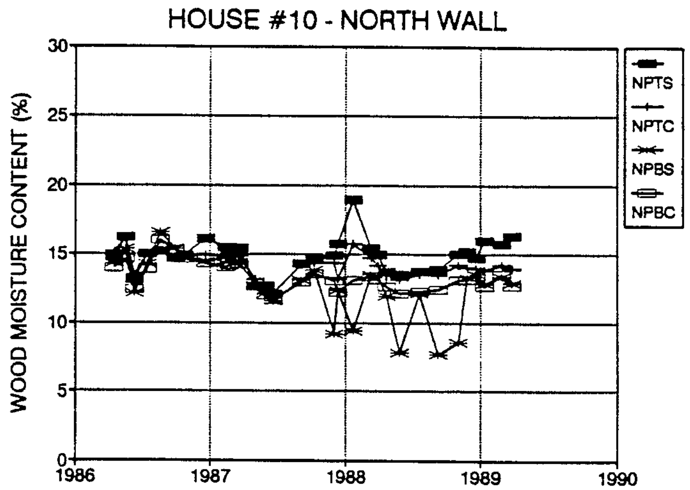
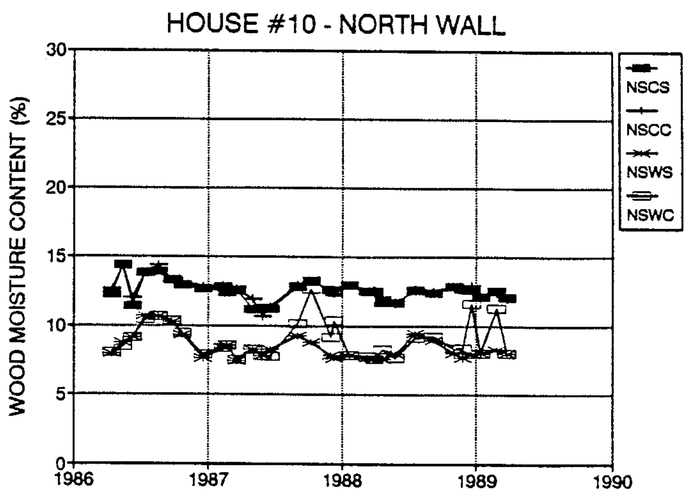
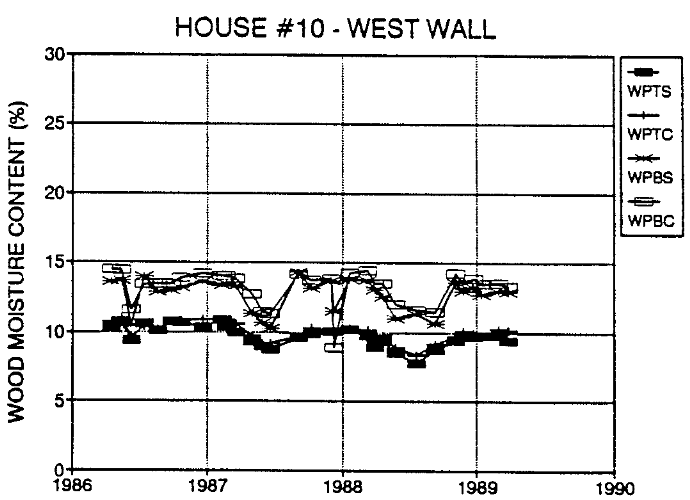
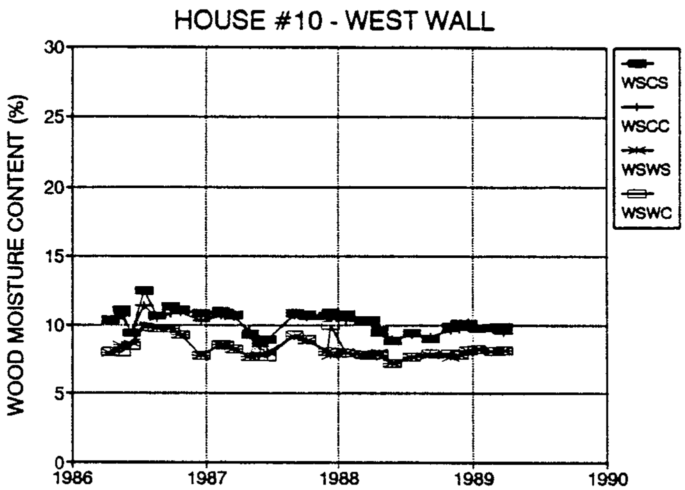
25
20
15
10
5
0
1986
1987
1988
1989
1990
SSCS
SSCC
SSWS
SSWC

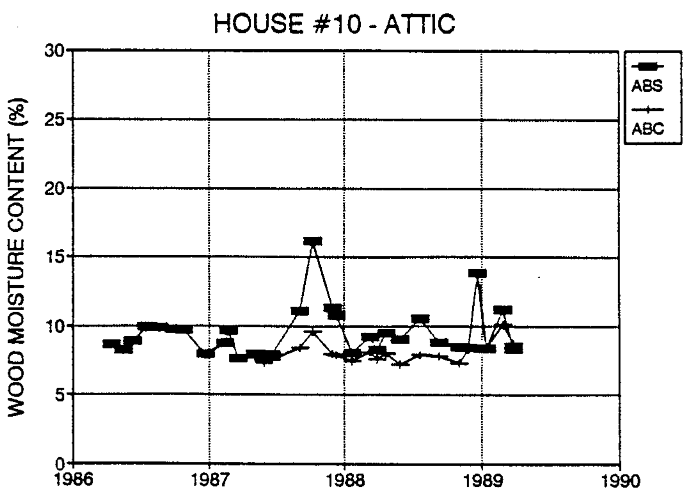

HOUSE #9 - ATTIC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ABS
ABC

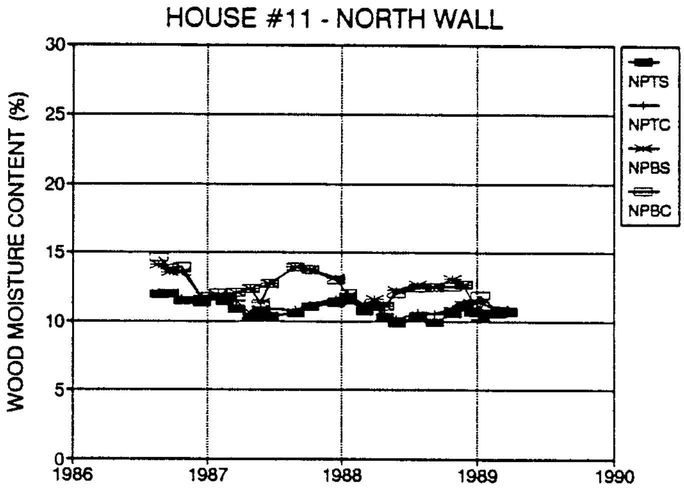

HOUSE #10 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

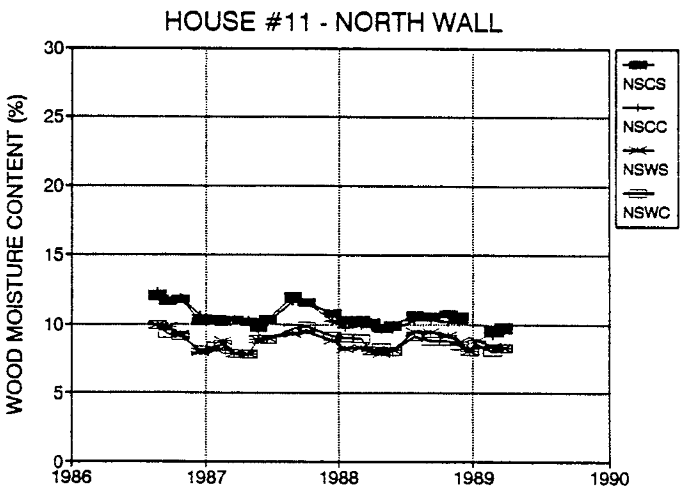

HOUSE #10 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

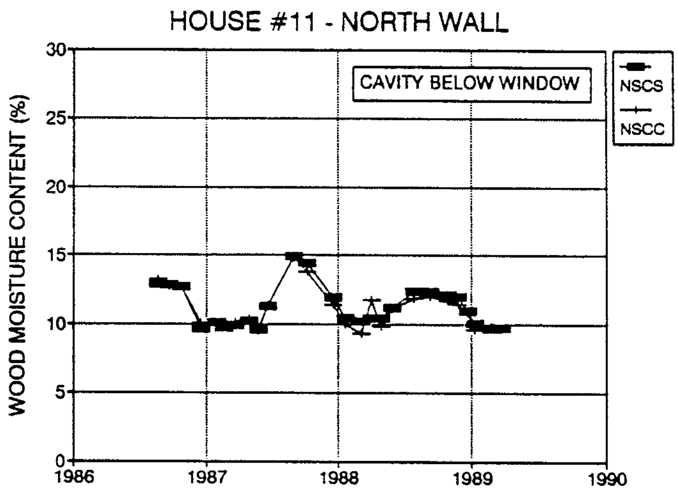

HOUSE #10 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WPTS
WPTC
WPBS
WPBC

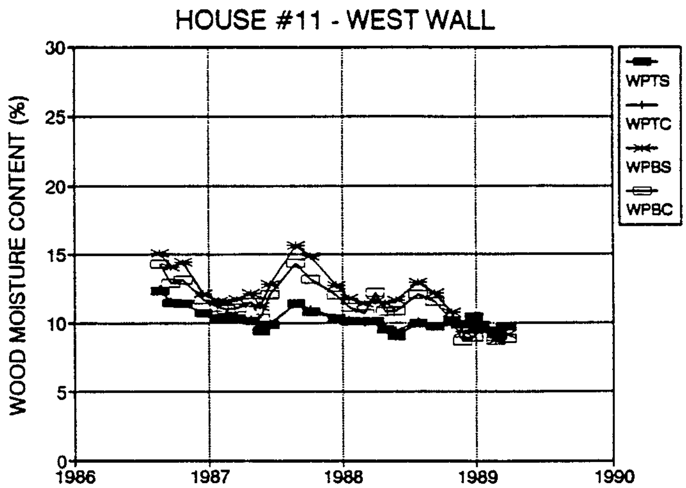

HOUSE #10 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WSCS
WSCC
WSWS
WSWC

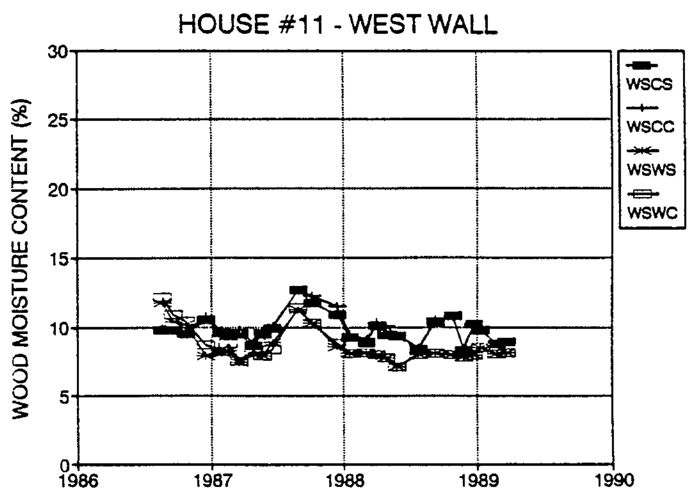

HOUSE #10 - ATTIC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ABS
ABC

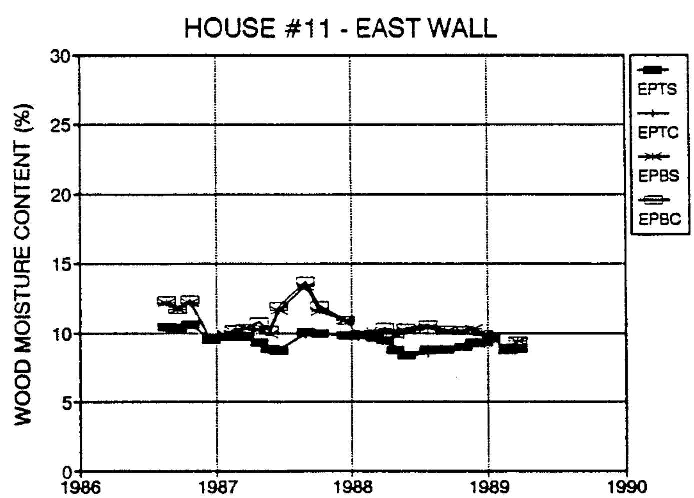

HOUSE #11 - NORTH WALL
WOOD MOISTURE CONTENT (%)
NPTS
NPTC
NPBS
NPBC

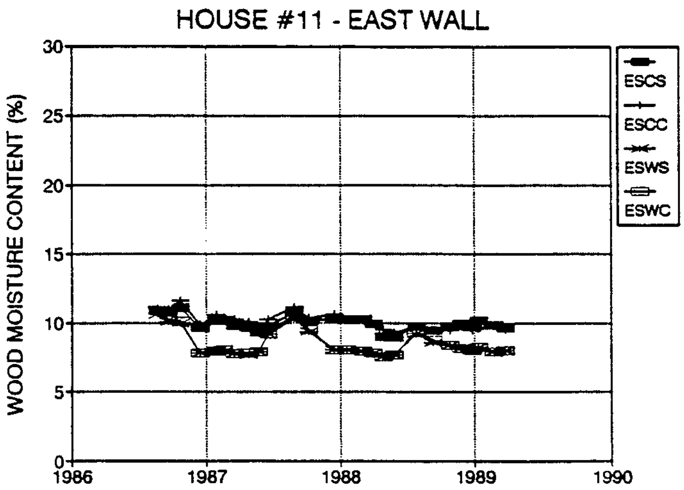

HOUSE #11 - NORTH WALL
WOOD MOISTURE CONTENT (%)
NSCS
NSCC
NSWS
NSWC

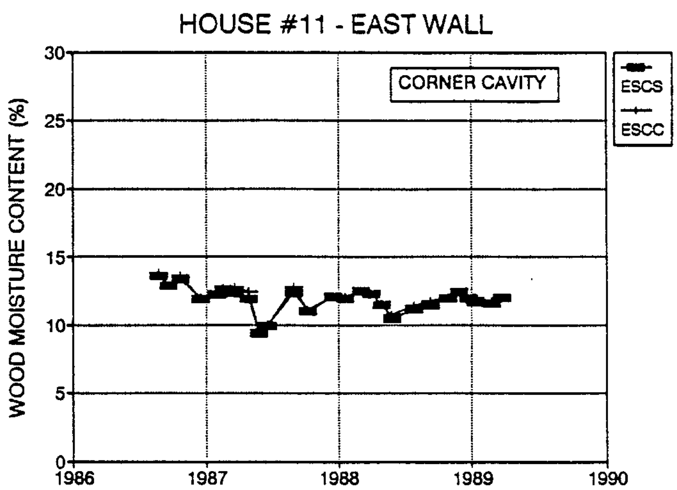

HOUSE #11 - NORTH WALL
WOOD MOISTURE CONTENT (%)
CAVITY BELOW WINDOW
NSCS
NSCC

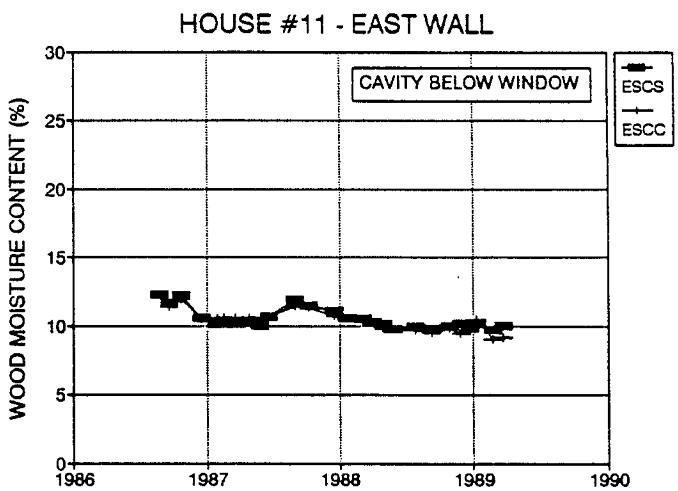

HOUSE #11 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WPTS
WPTC
WPBS
WPBC

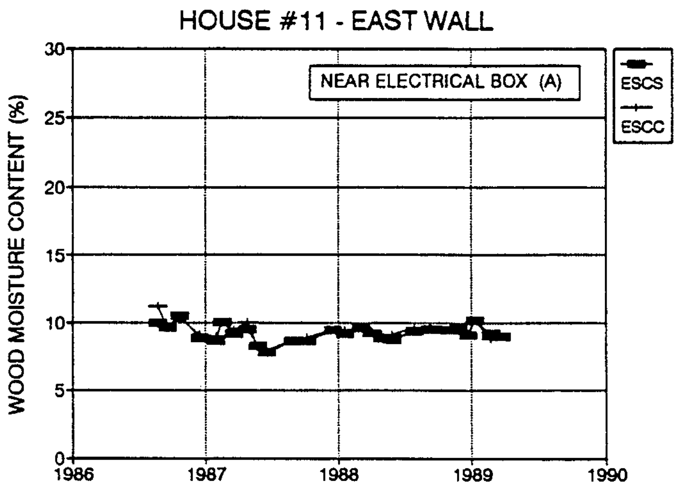

HOUSE #11 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WSCS
WSCC
WSWS
WSWC


HOUSE #11 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
EPBC

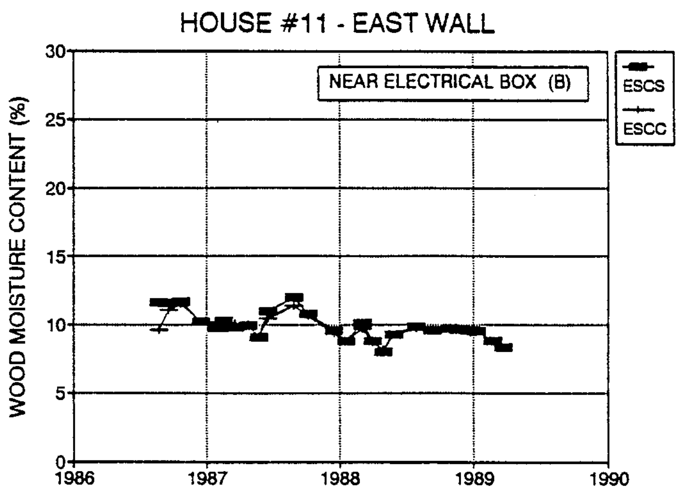

HOUSE #11 - EAST WALL
WOOD MOISTURE CONTENT (%)
ESCS
ESCC
ESWS
ESWC
30
25
20
15
10
5
0
1986
1987
1988
1989
1990


HOUSE #11 - EAST WALL
CORNER CAVITY
WOOD MOISTURE CONTENT (%)
ESCS
ESCC
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

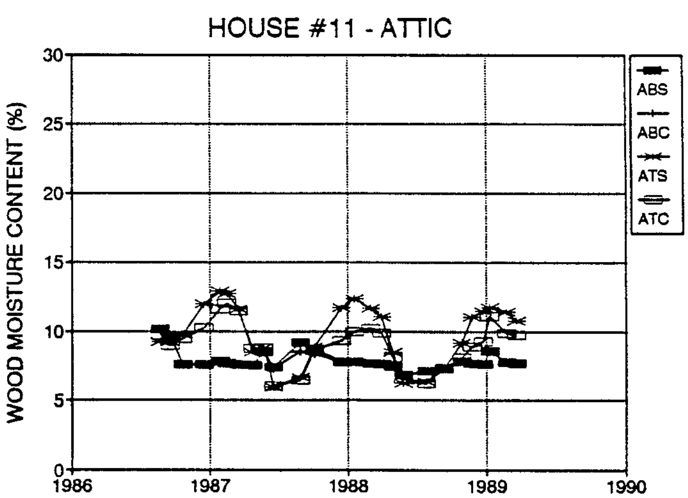

HOUSE #11 - EAST WALL
CAVITY BELOW WINDOW
WOOD MOISTURE CONTENT (%)
ESCS
ESCC
30
25
20
15
10
5
0
1986
1987
1988
1989
1990



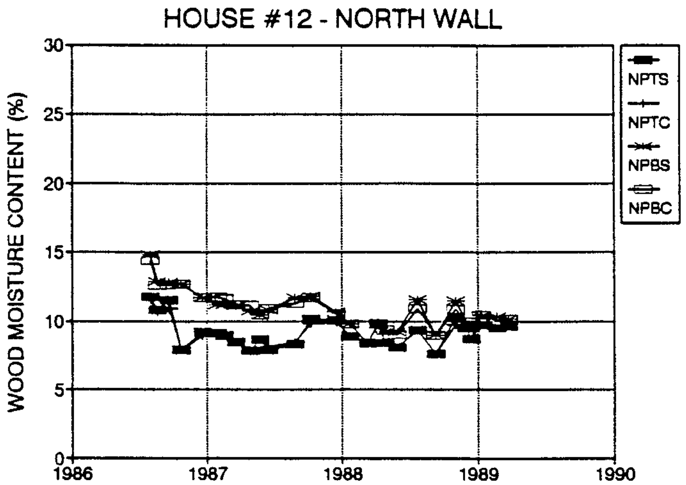
HOUSE #11 - EAST WALL
NEAR ELECTRICAL BOX (A)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

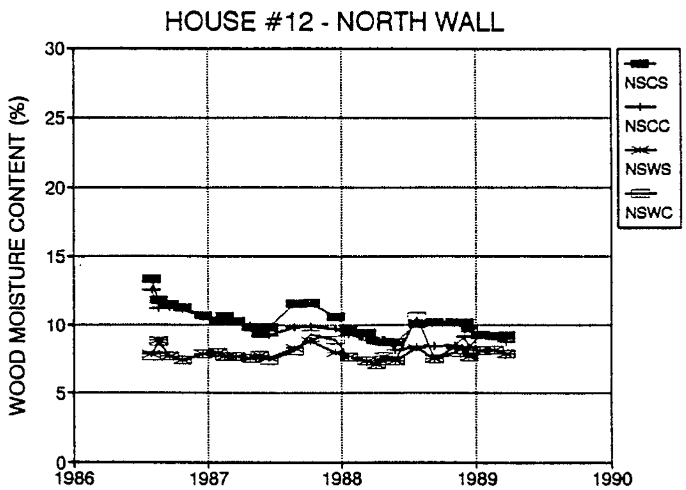


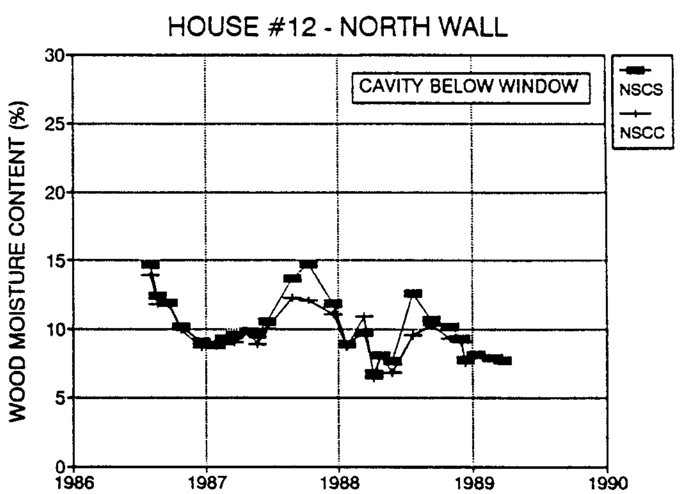
HOUSE #11 - EAST WALL
NEAR ELECTRICAL BOX (B)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

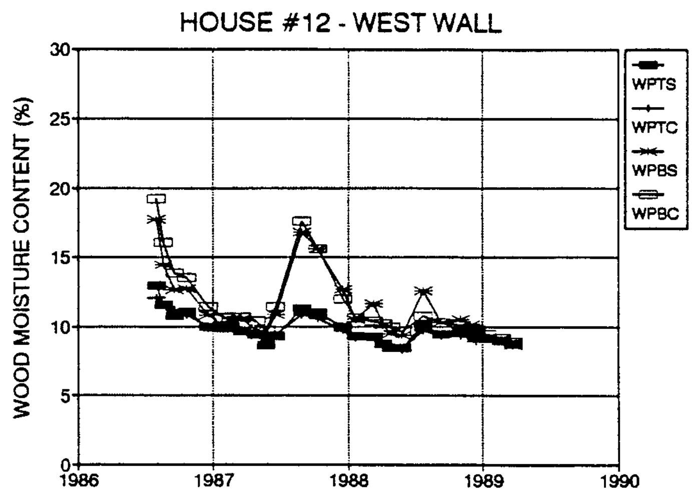


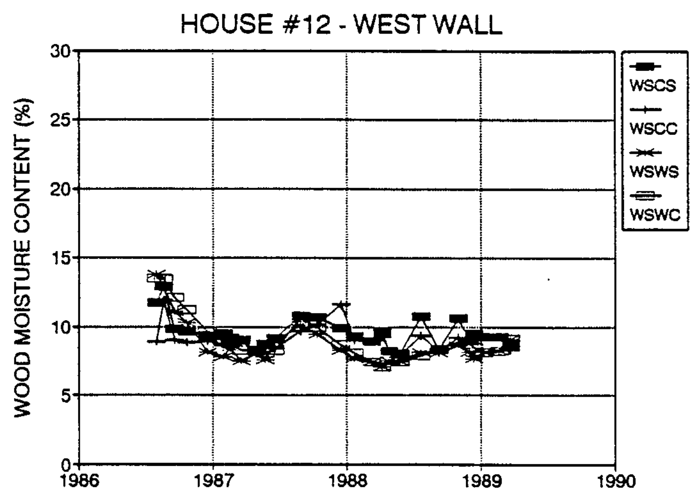
HOUSE #11 - ATTIC
ABS
ABC
ATS
ATC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

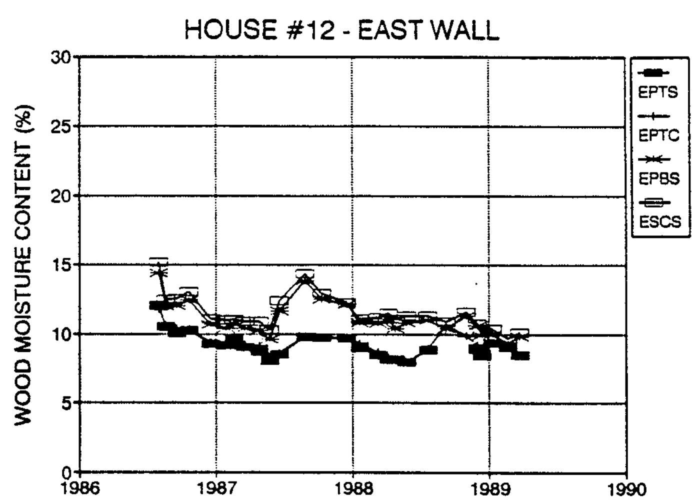

HOUSE #12 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

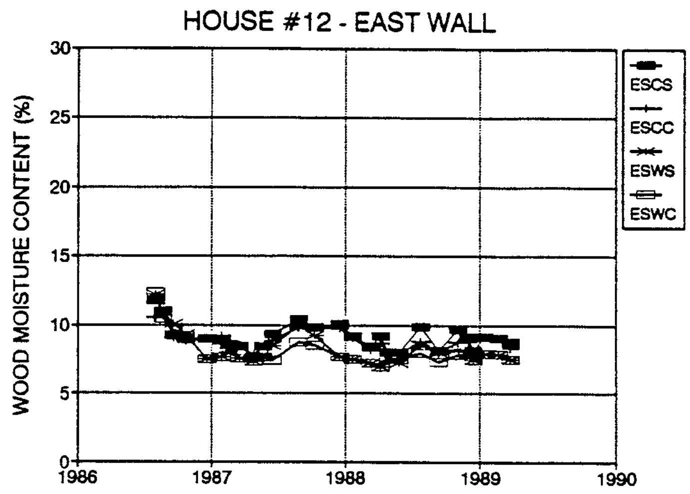

HOUSE #12 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

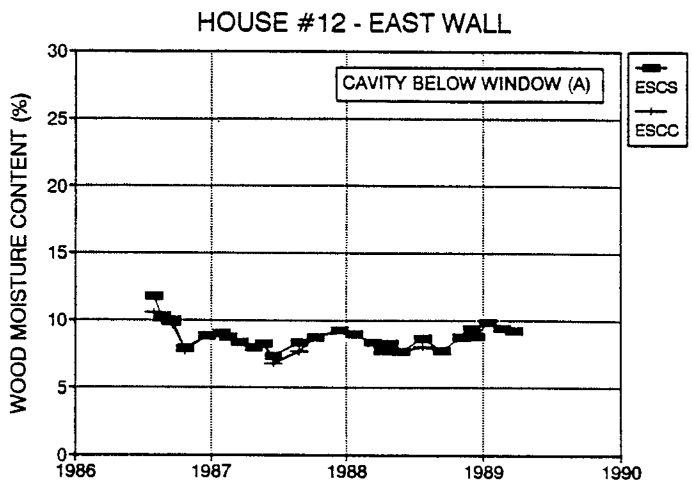

HOUSE #12 - NORTH WALL
CAVITY BELOW WINDOW
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC

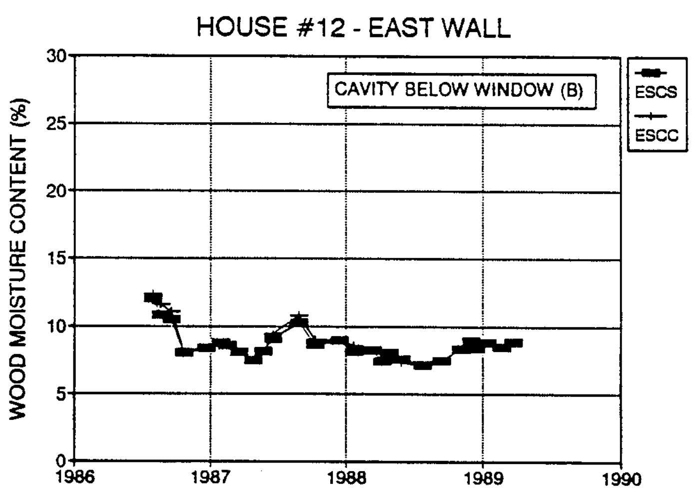

HOUSE #12 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WPTS
WPTC
WPBS
WPBC

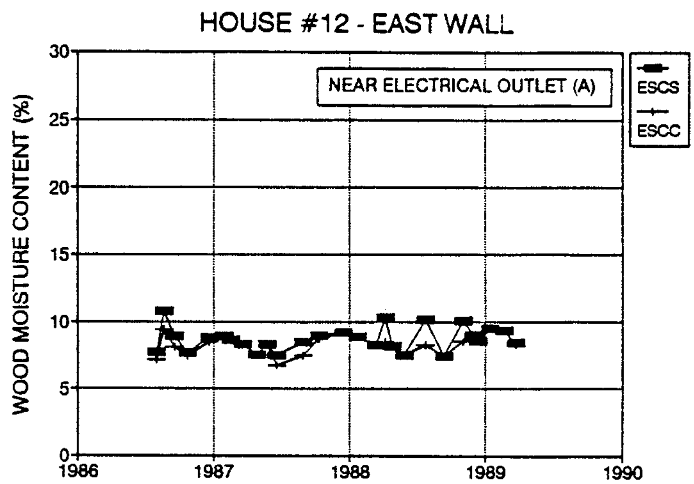

HOUSE #12 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
WSCS
WSCC
WSWS
WSWC

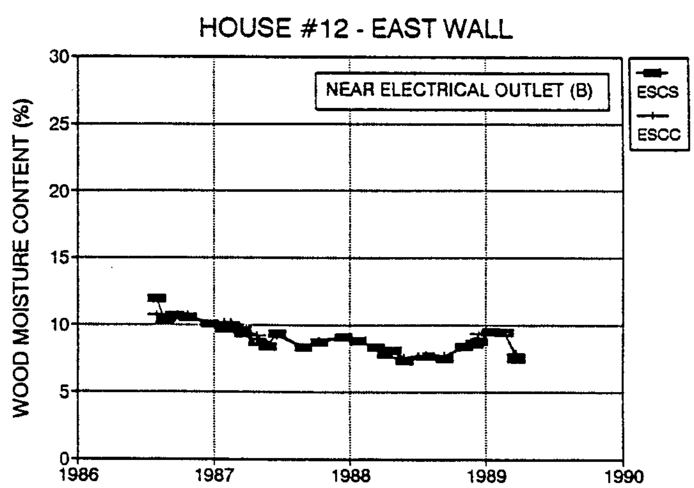

HOUSE #12 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
ESCS

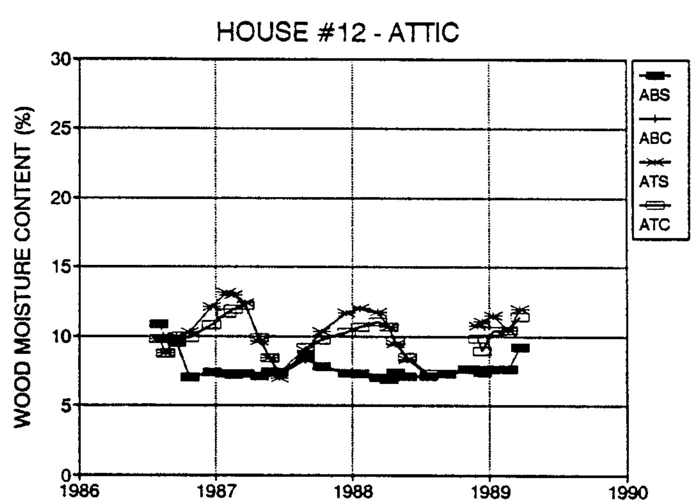

HOUSE #12 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC
ESWS
ESWC

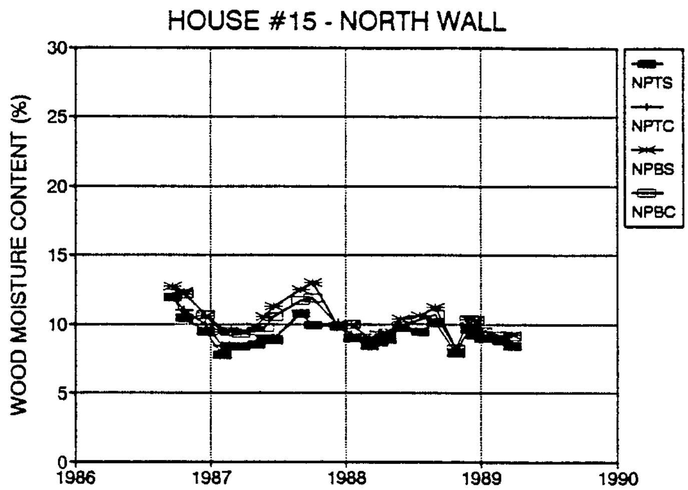

HOUSE #12 - EAST WALL
CAVITY BELOW WINDOW (A)
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

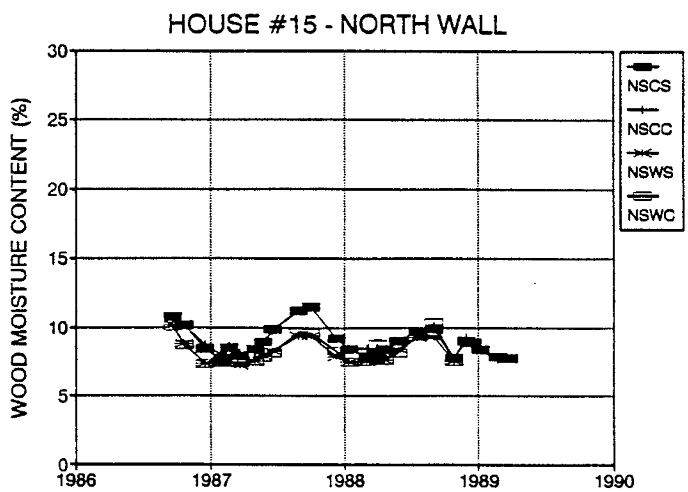

HOUSE #12 - EAST WALL
CAVITY BELOW WINDOW (B)
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

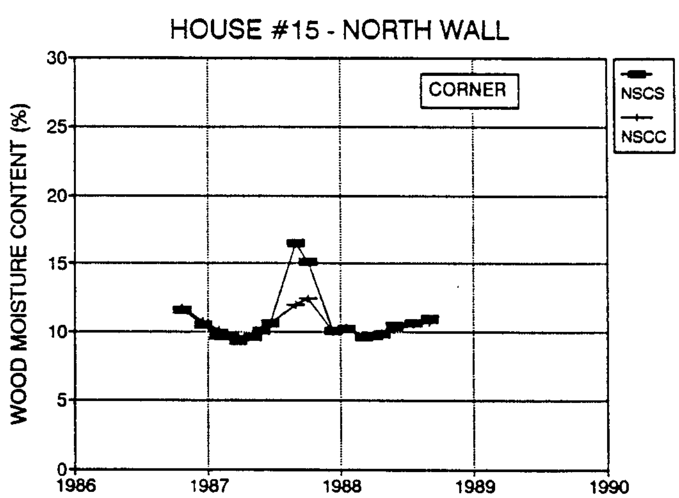

HOUSE #12 - EAST WALL
NEAR ELECTRICAL OUTLET (A)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

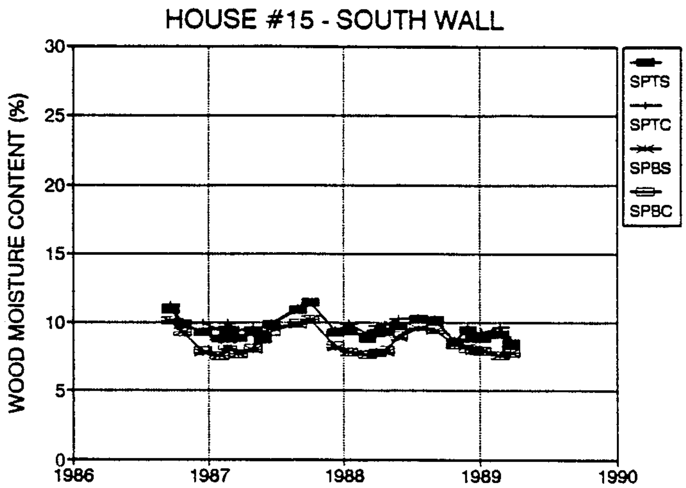

HOUSE #12 - EAST WALL
NEAR ELECTRICAL OUTLET (B)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

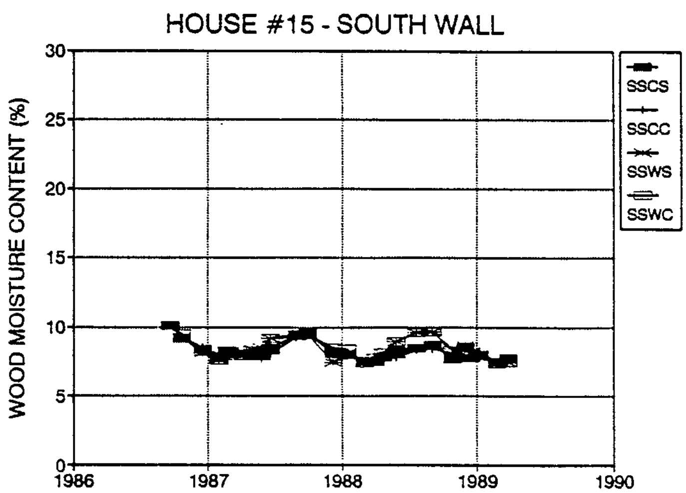

HOUSE #12 - ATTIC
ABS
ABC
ATS
ATC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

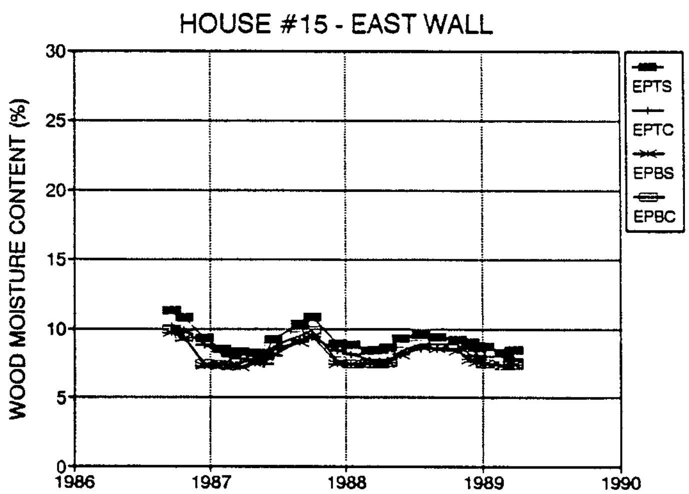

HOUSE #15 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

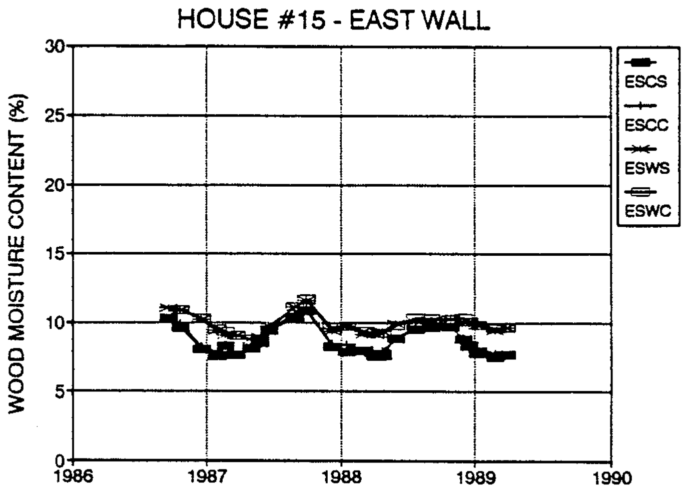

HOUSE #15 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

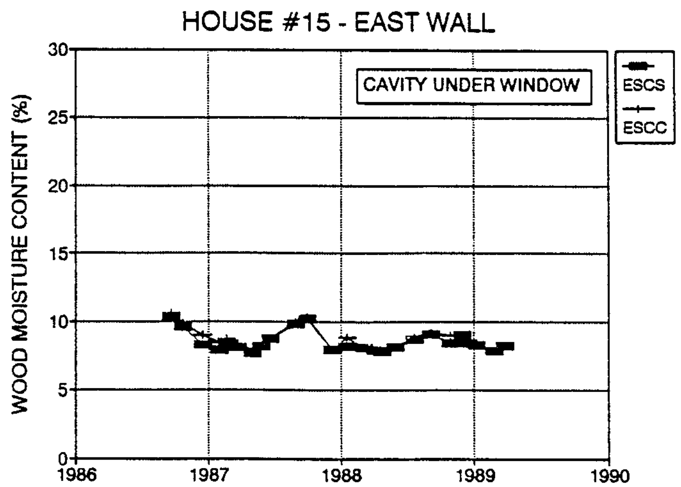

HOUSE #15 - NORTH WALL
CORNER
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC

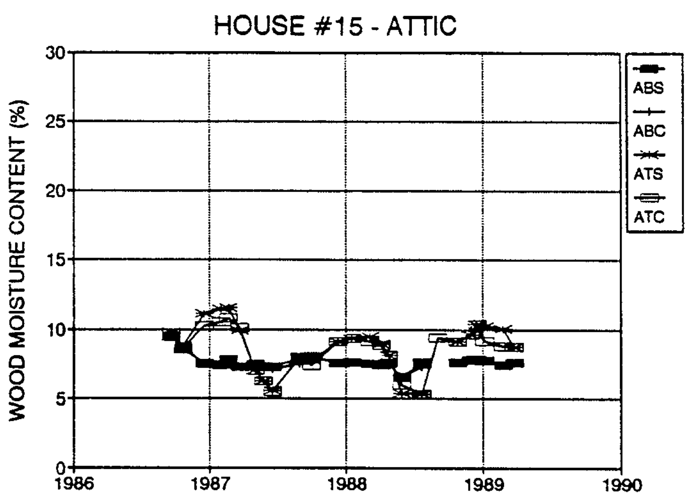

HOUSE #15 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SPTS
SPTC
SPBS
SPBC

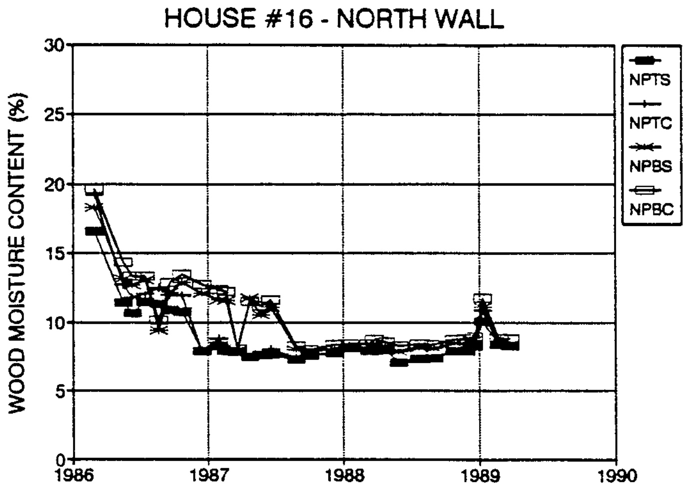

HOUSE #15 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SSCS
SSCC
SSWS
SSWC

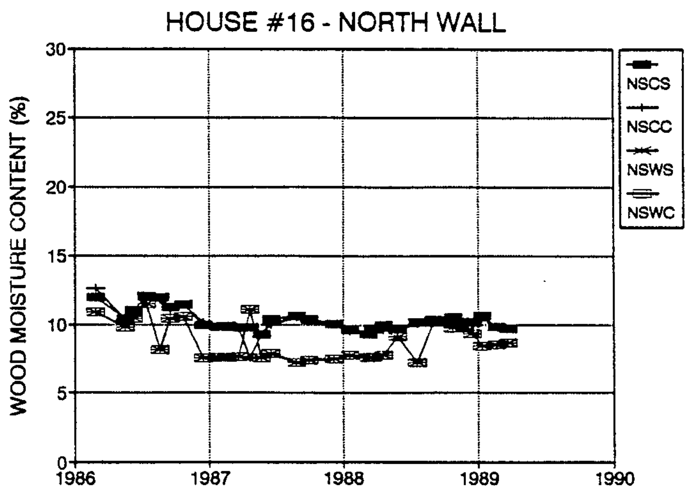

HOUSE #15 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
EPBC

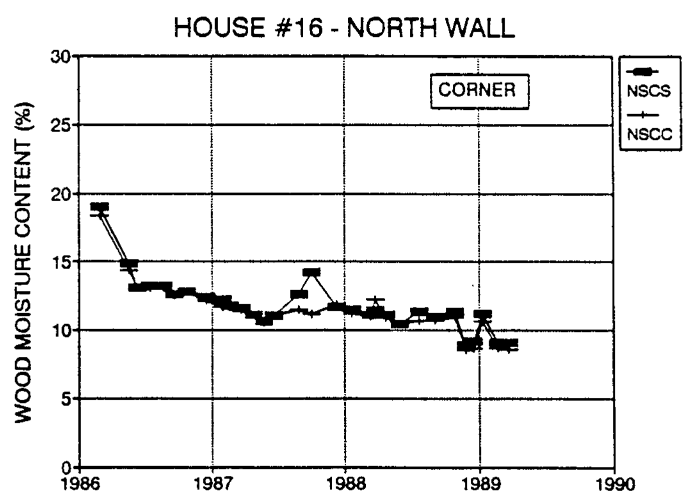

HOUSE #15 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC
ESWS
ESWC

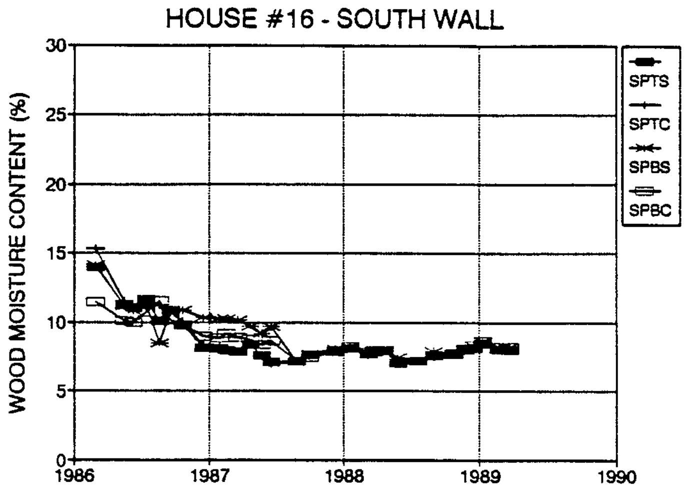

HOUSE #15 - EAST WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

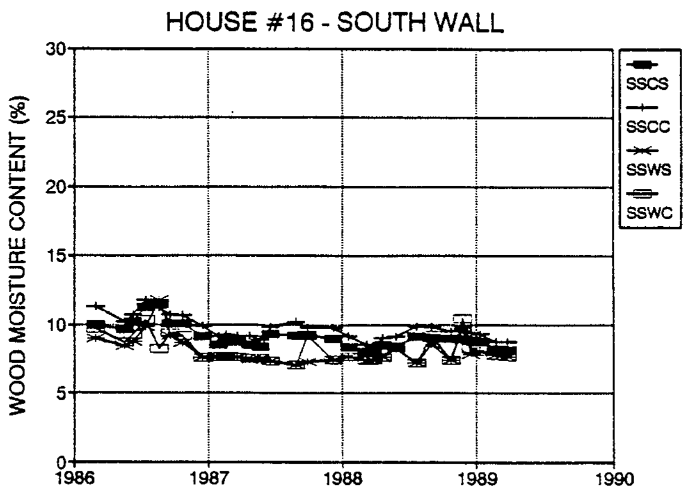

HOUSE #15 - ATTIC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ABS
ABC
ATS
ATC

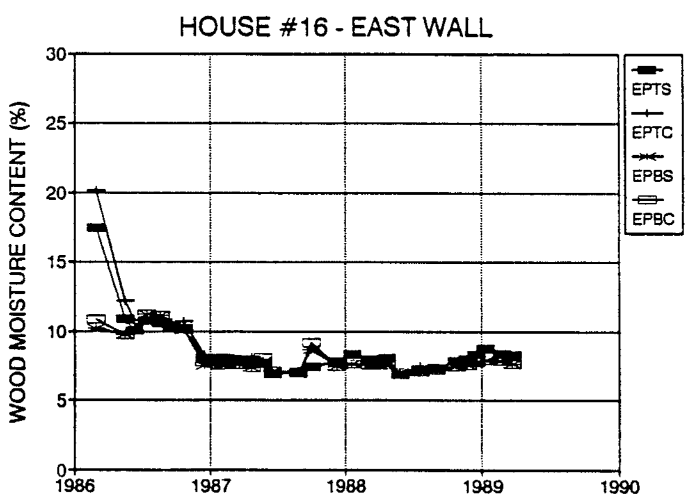

HOUSE #16 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

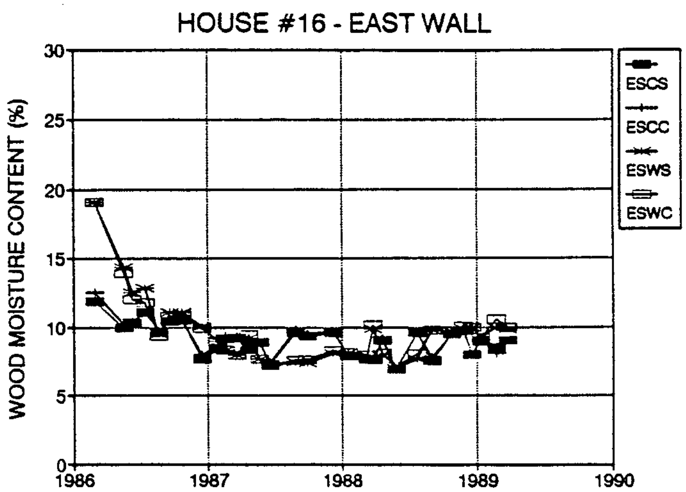

HOUSE #16 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

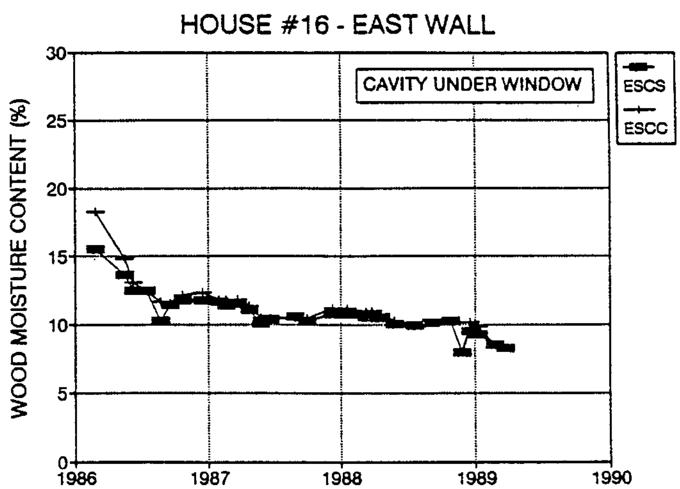

HOUSE #16 - NORTH WALL
CORNER
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC

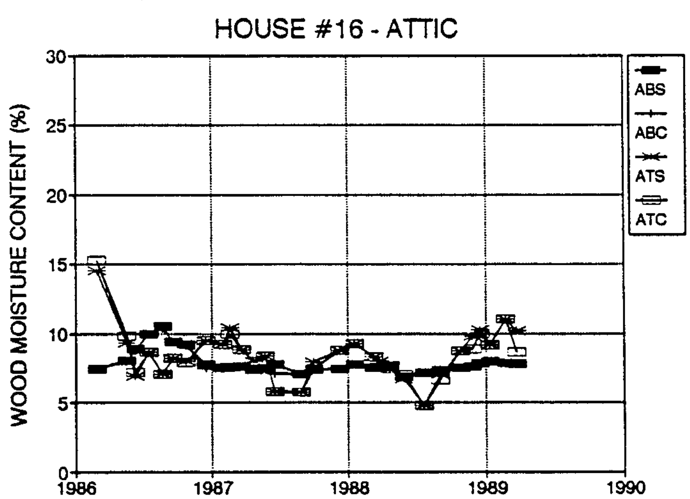

HOUSE #16 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SPTS
SPTC
SPBS
SPBC

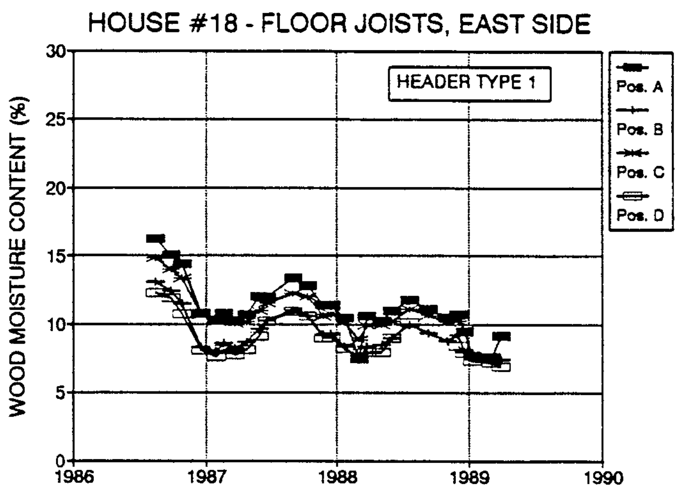

HOUSE #16 - SOUTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
SSCS
SSCC
SSWS
SSWC

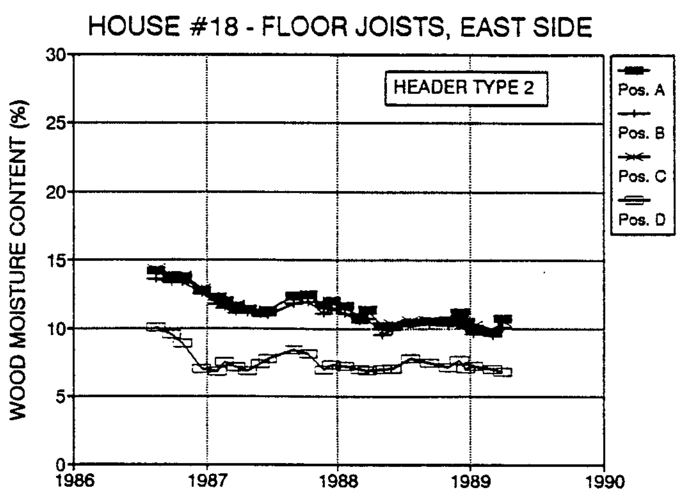

HOUSE #16 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
EPBC

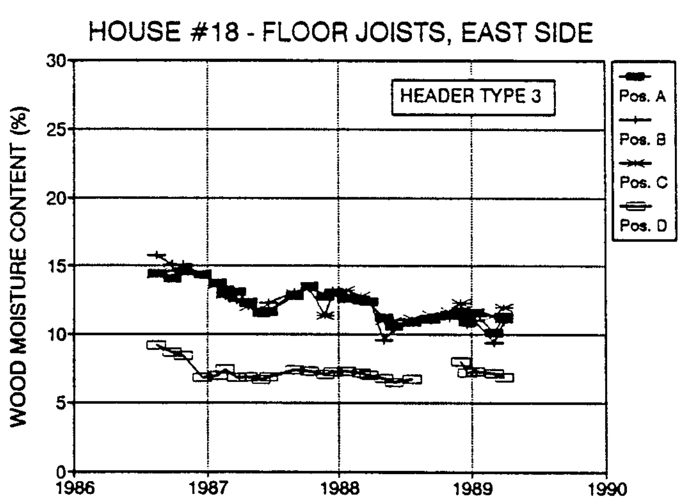

HOUSE #16 - EAST WALL
WOOD MOISTURE CONTENT (%)
ESCS
ESCC
ESWS
ESWC
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

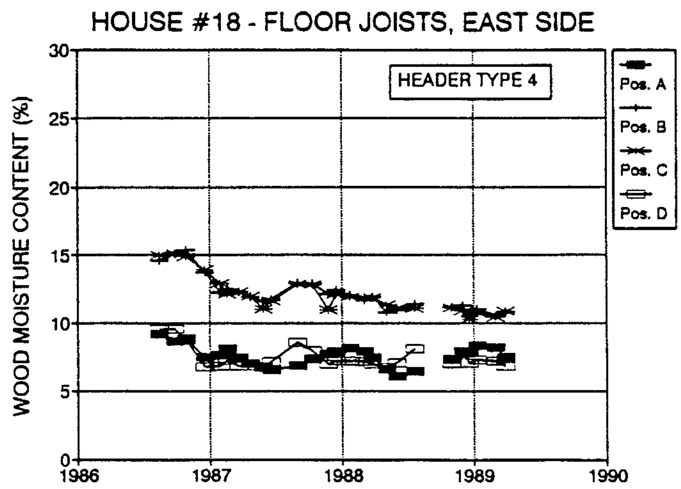

HOUSE #16 - EAST WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
ESCS
ESCC
0
5
10
15
20
25
30
1986
1987
1988
1989
1990


HOUSE #16 - ATTIC
WOOD MOISTURE CONTENT (%)
ABS
ABC
ATS
ATC
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

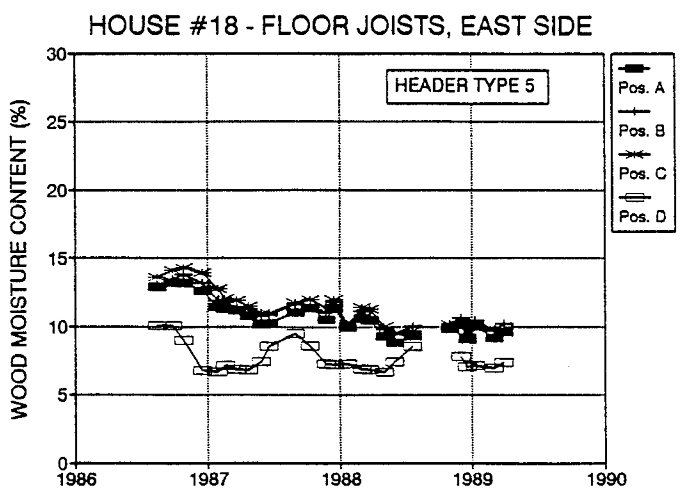

HOUSE #18 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 1
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D


HOUSE #18 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 2
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

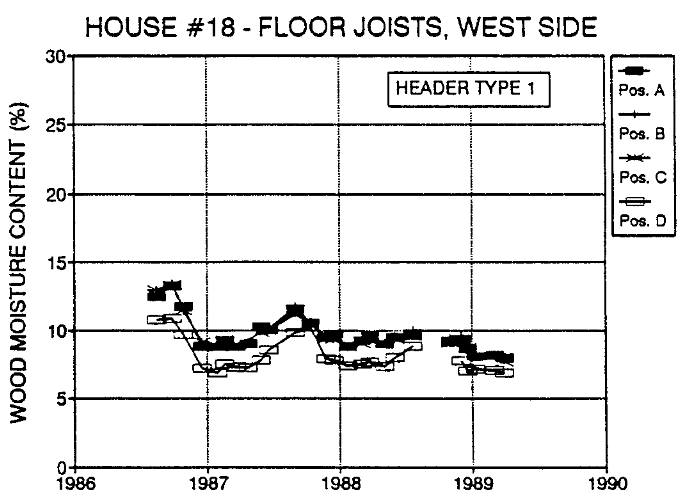

HOUSE #18 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 3
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D



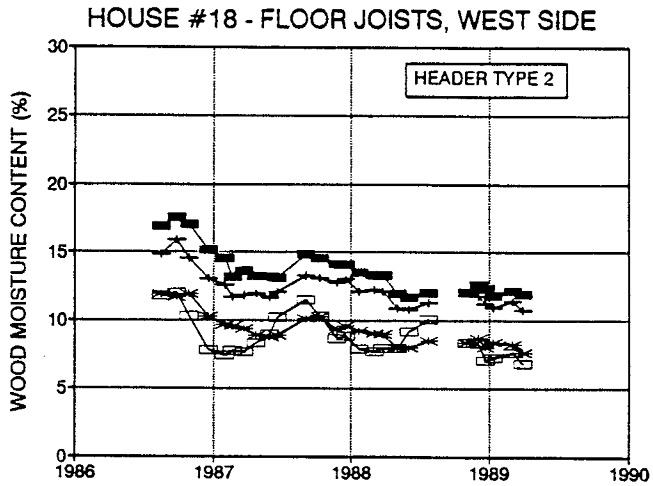
HOUSE #18 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 4
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

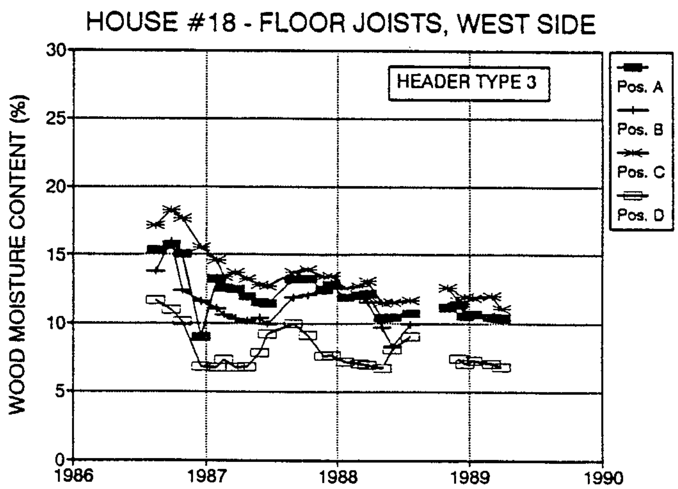


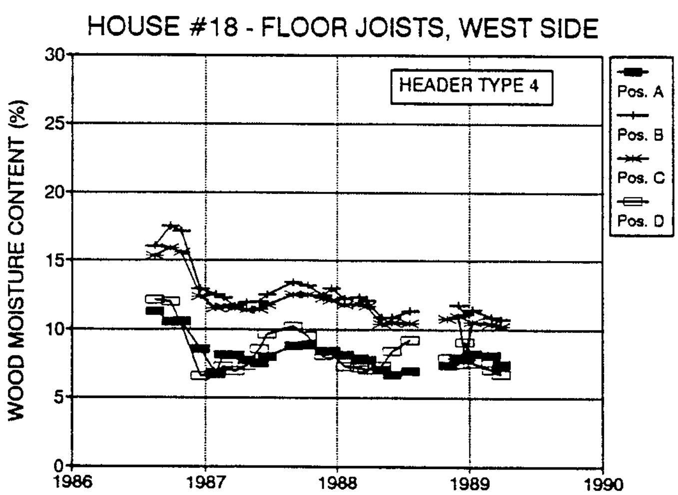
HOUSE #18 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 5
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

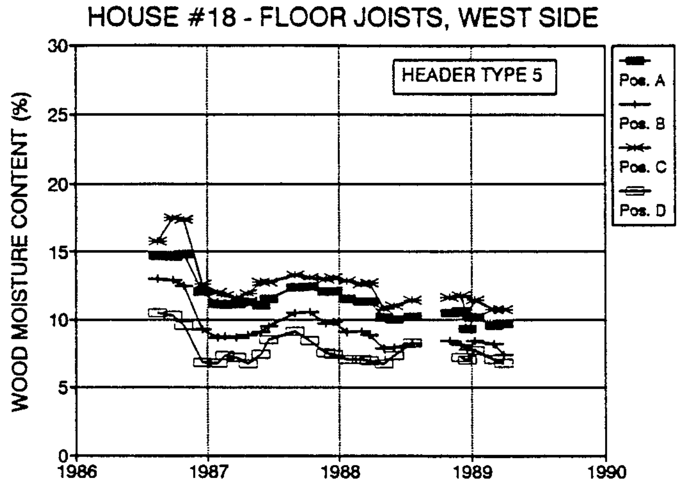


HOUSE #18 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 1
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

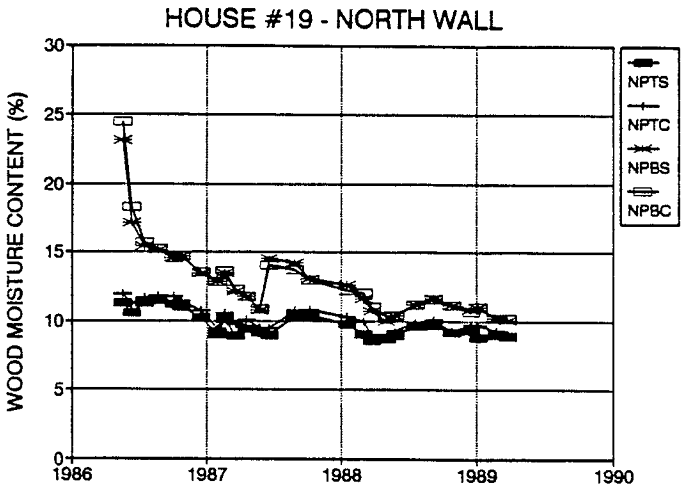

HOUSE #18 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 2
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

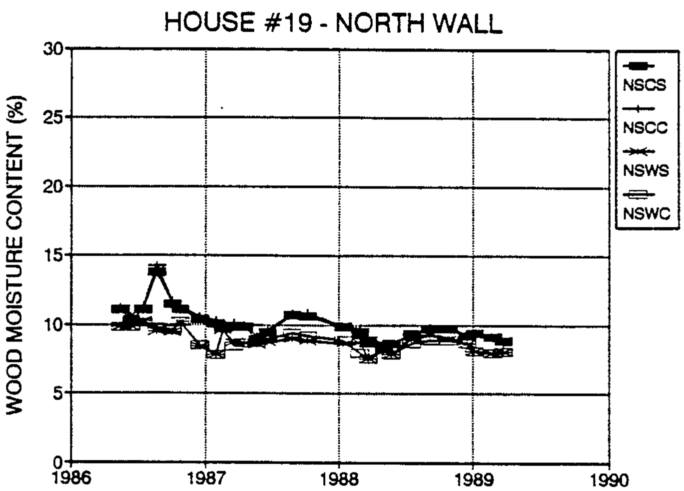

HOUSE #18 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 3
Pos. A
Pos. B
Pos. C
Pos. D
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

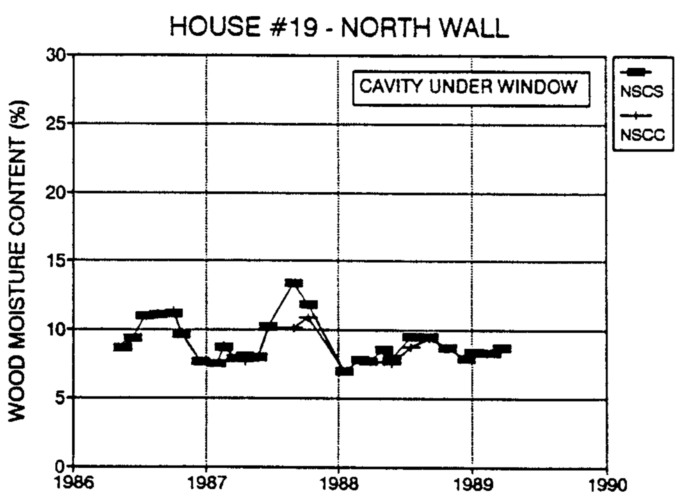

HOUSE #18 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 4
Pos. A
Pos. B
Pos. C
Pos. D
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

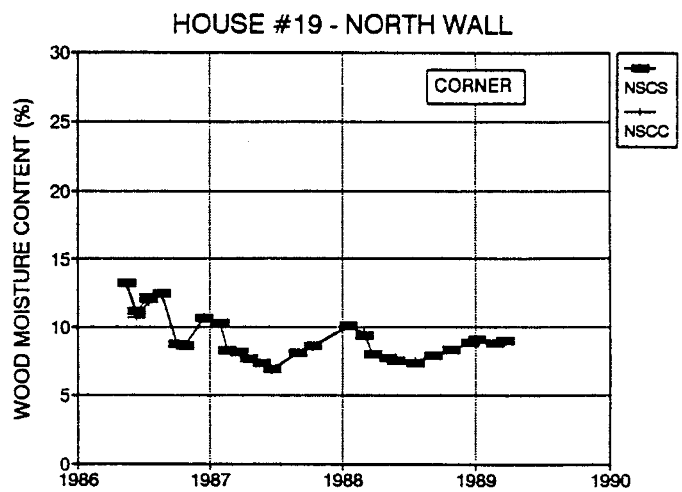


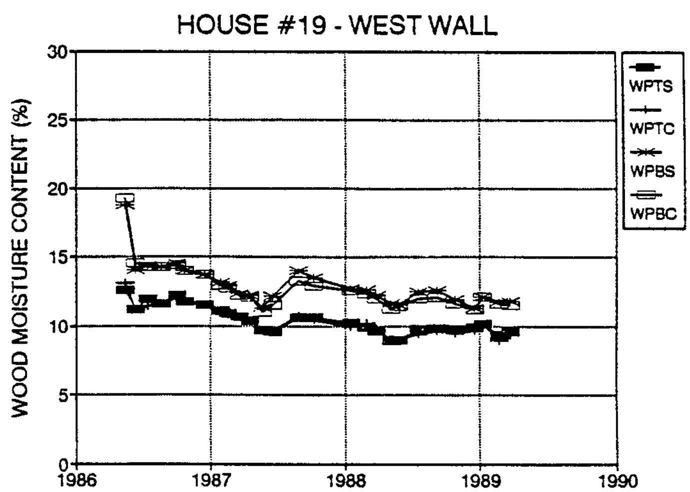
HOUSE #18 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 5
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

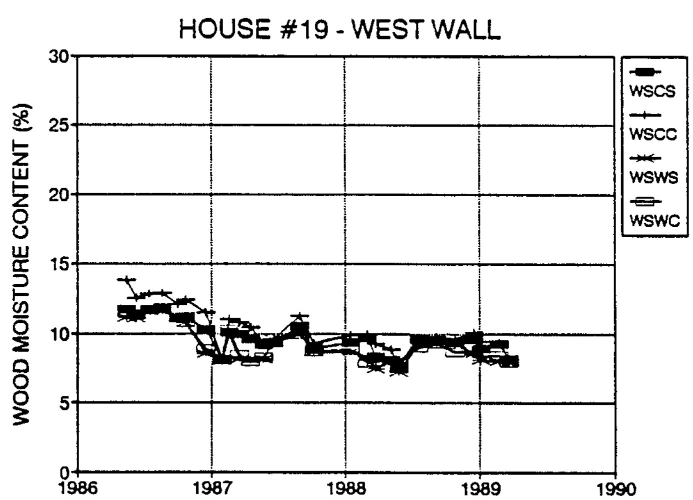

HOUSE #19 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

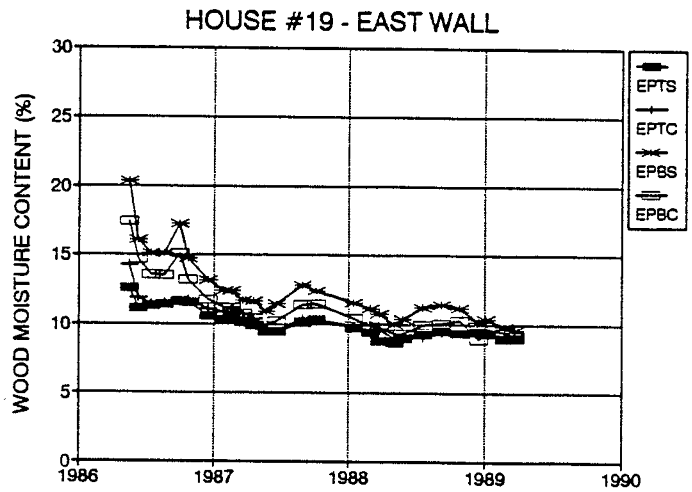

HOUSE #19 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC

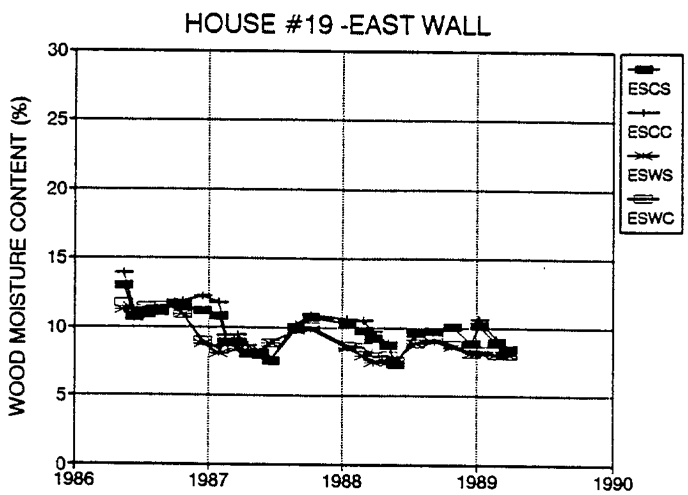

HOUSE #19 - NORTH WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
NSCS
NSCC

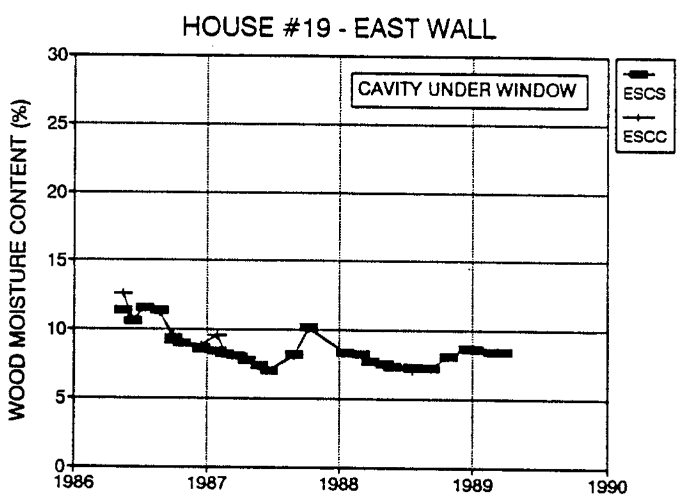

HOUSE #19 - NORTH WALL
CORNER
NSCS
NSCC
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

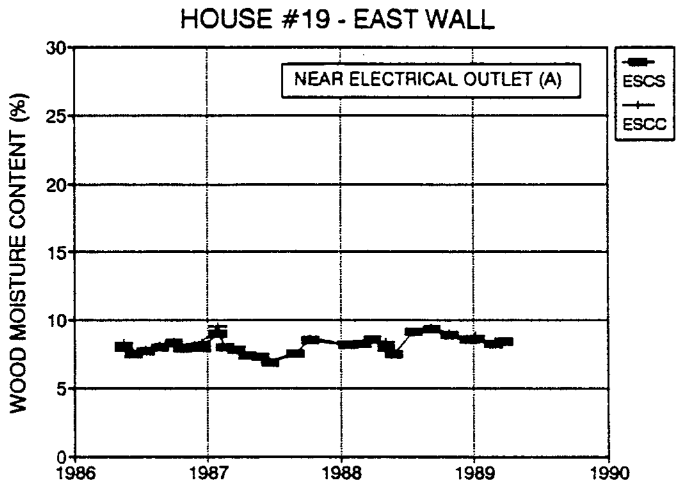

HOUSE #19 - WEST WALL
WPTS
WPTC
WPBS
WPBC
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

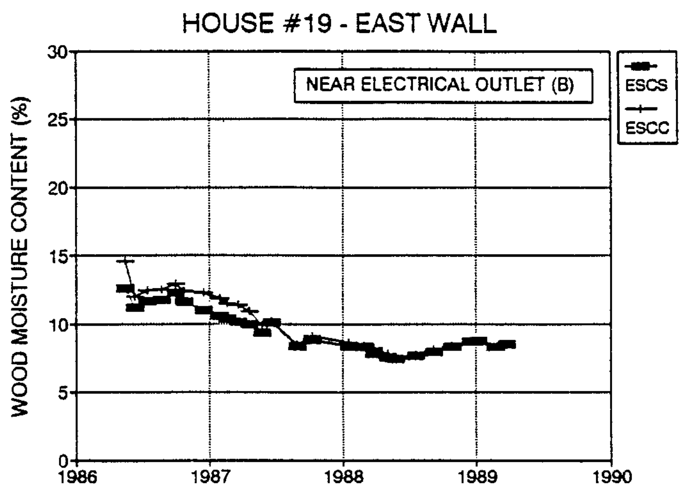

HOUSE #19 - WEST WALL
WSCS
WSCC
WSWS
WSWC
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

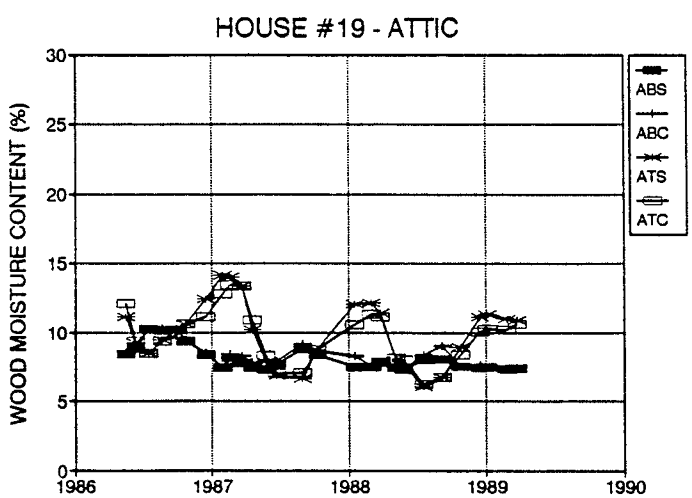

HOUSE #19 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
EPBC

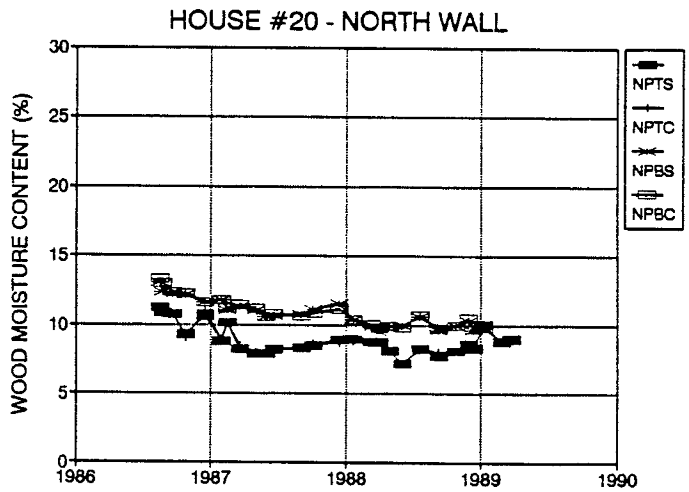

HOUSE #19 -EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC
ESWS
ESWC

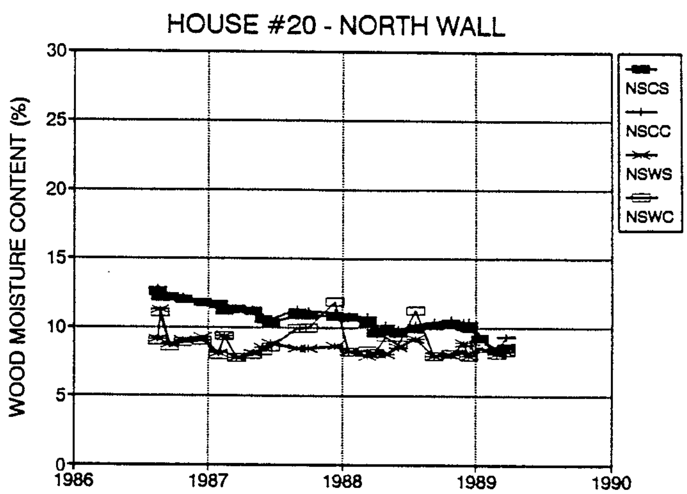

HOUSE #19 - EAST WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

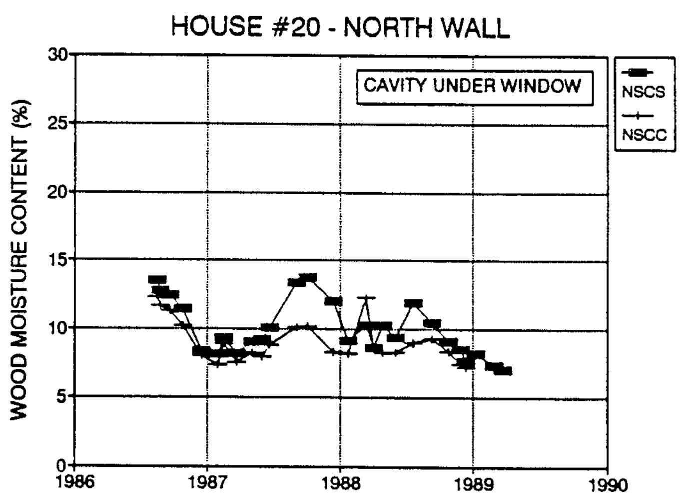

HOUSE #19 - EAST WALL
NEAR ELECTRICAL OUTLET (A)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

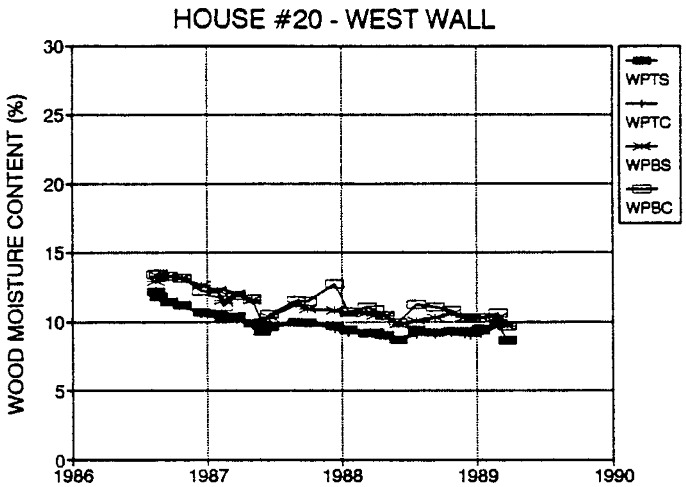

HOUSE #19 - EAST WALL
NEAR ELECTRICAL OUTLET (B)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

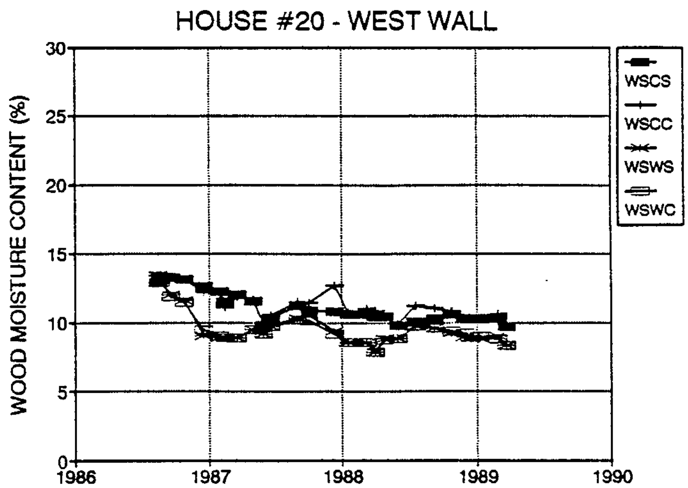

HOUSE #19 - ATTIC
ABS
ABC
ATS
ATC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

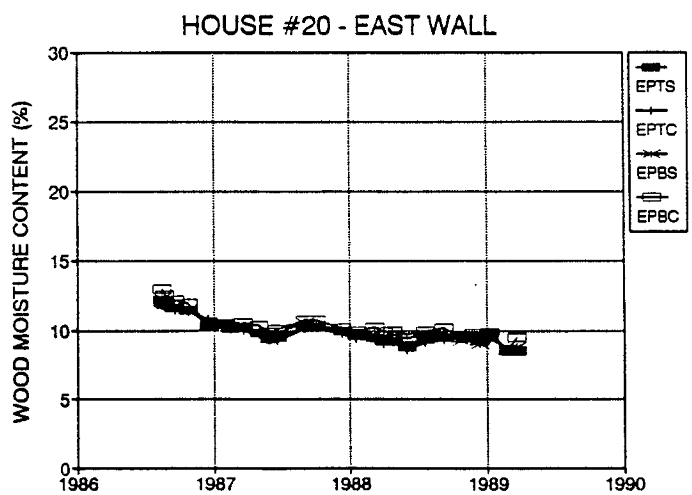

HOUSE #20 - NORTH WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
NPTS
NPTC
NPBS
NPBC

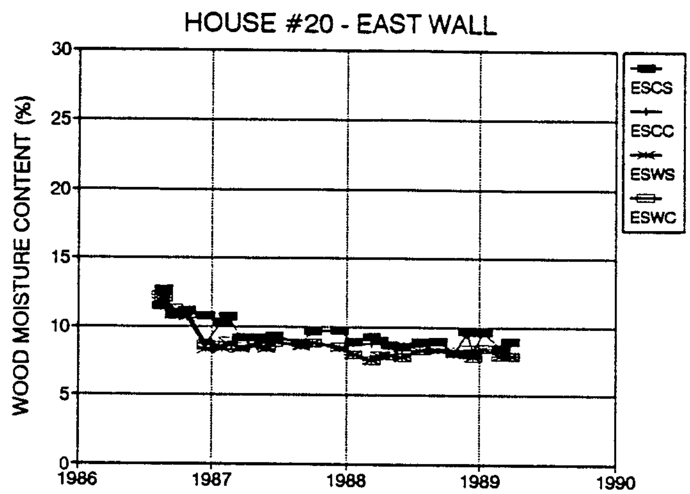

HOUSE #20 - NORTH WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
NSCS
NSCC
NSWS
NSWC


HOUSE #20 - NORTH WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
NSCS
NSCC

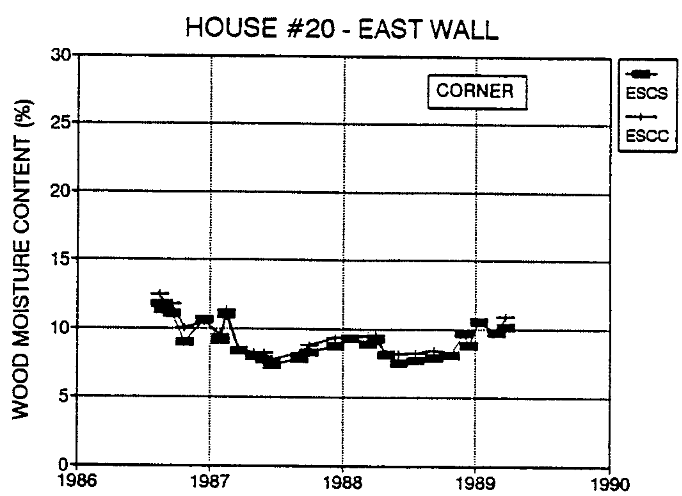

HOUSE #20 - WEST WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
WPTS
WPTC
WPBS
WPBC


HOUSE #20 - WEST WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
WSCS
WSCC
WSWS
WSWC

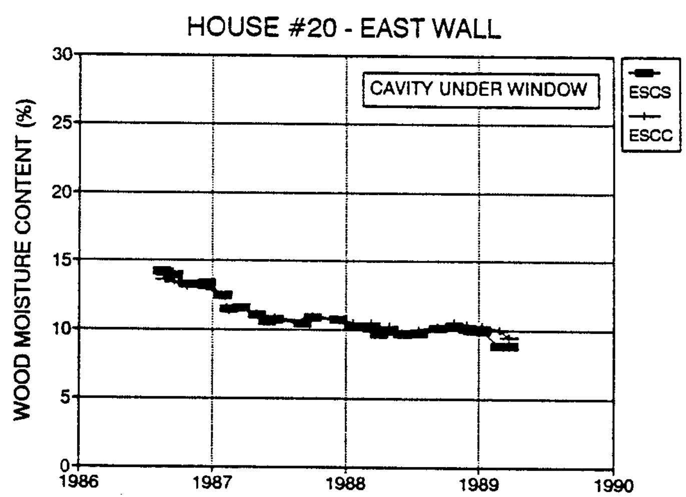

HOUSE #20 - EAST WALL
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
EPTS
EPTC
EPBS
EPBC



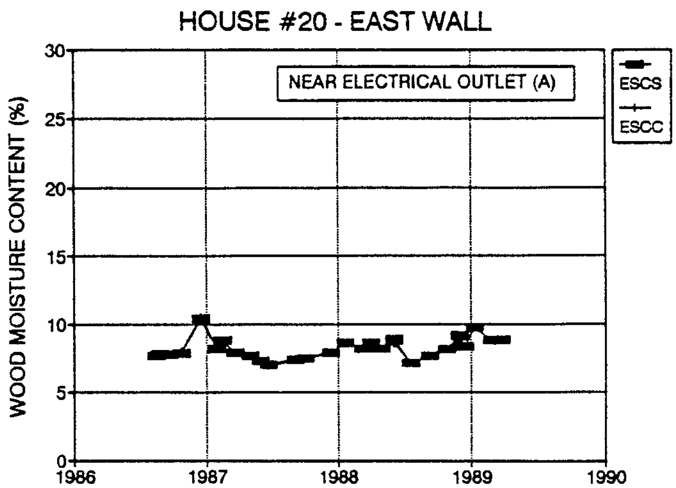
HOUSE #20 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC
ESWS
ESWC

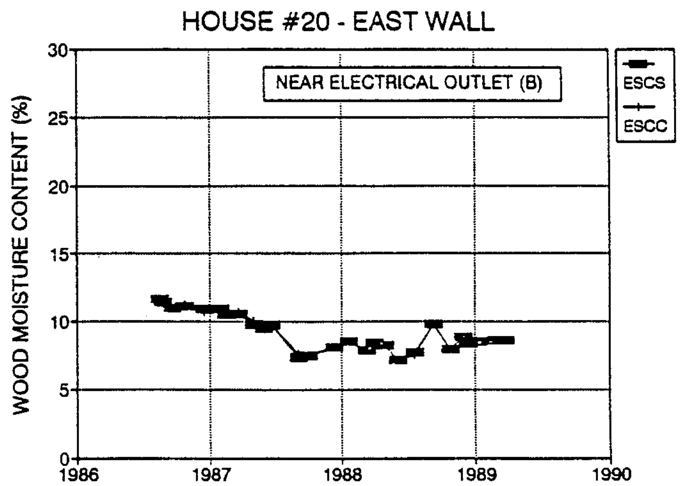


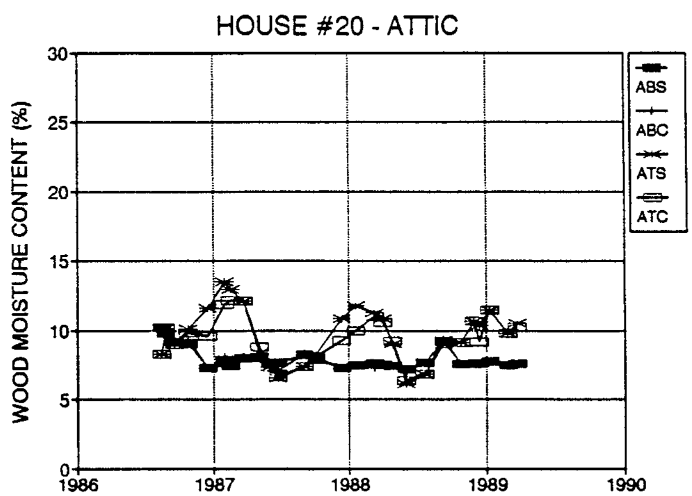
HOUSE #20 - EAST WALL
CORNER
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

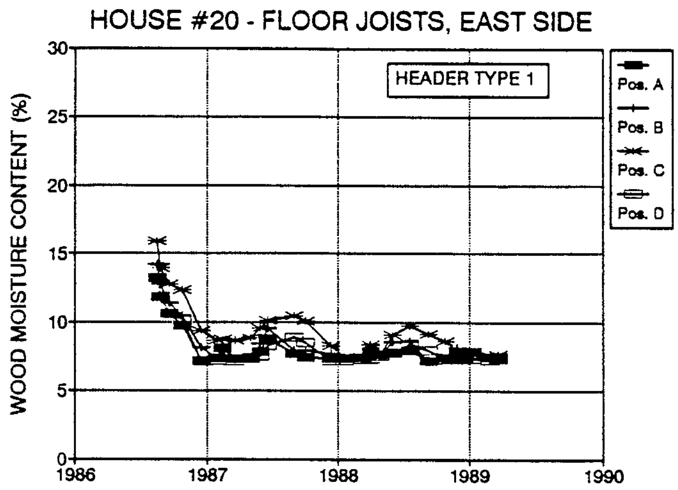


HOUSE #20 - EAST WALL
CAVITY UNDER WINDOW
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
ESCS
ESCC

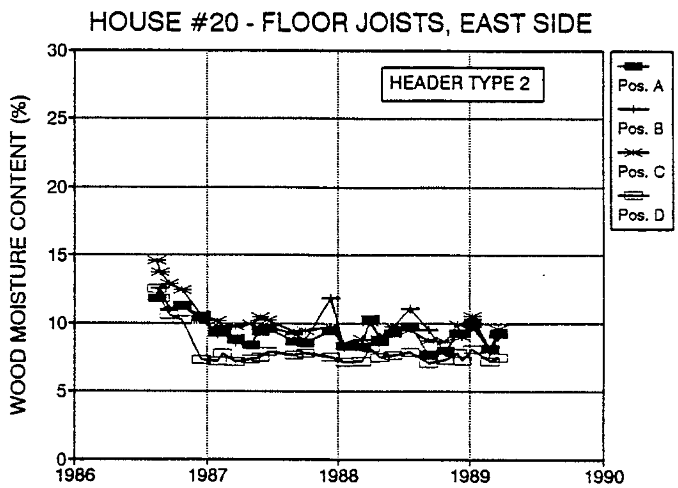

HOUSE #20 - EAST WALL
NEAR ELECTRICAL OUTLET (A)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990


HOUSE #20 - EAST WALL
NEAR ELECTRICAL OUTLET (B)
ESCS
ESCC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990

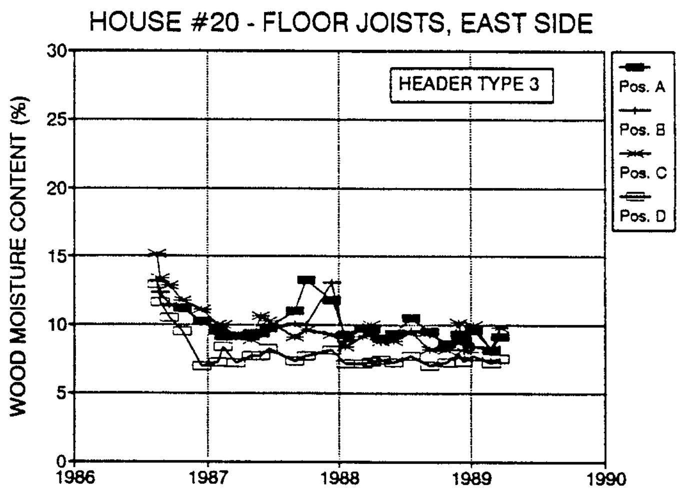

HOUSE #20 - ATTIC
ABS
ABC
ATS
ATC
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990



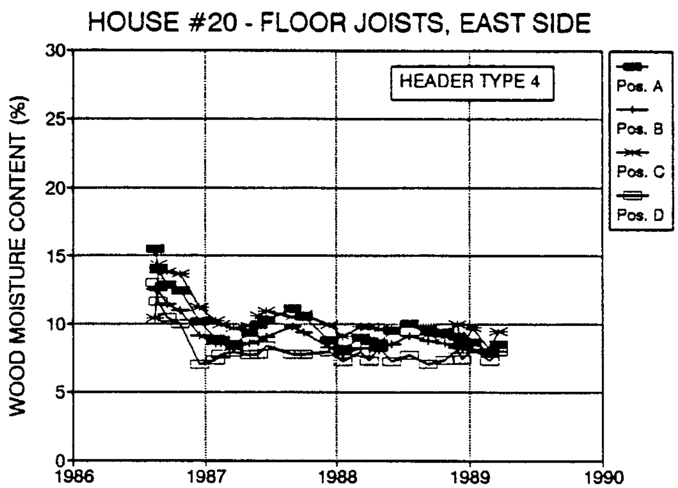
HOUSE #20 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 1
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

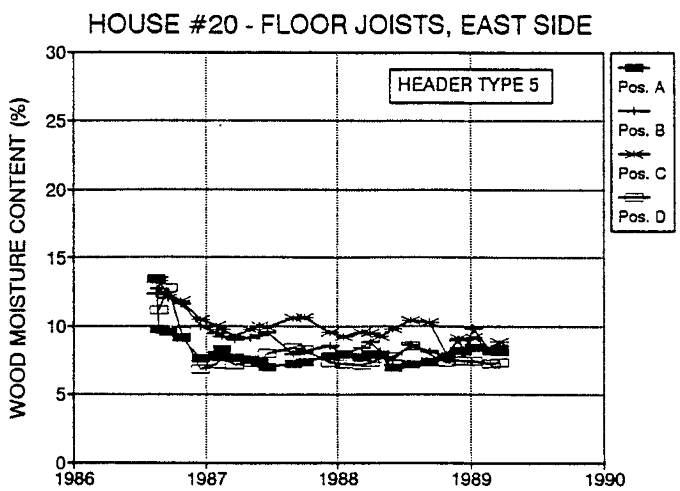


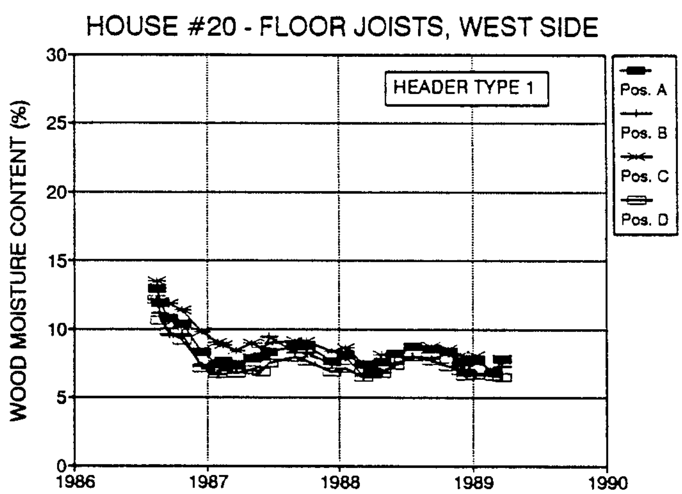
HOUSE #20 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 2
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

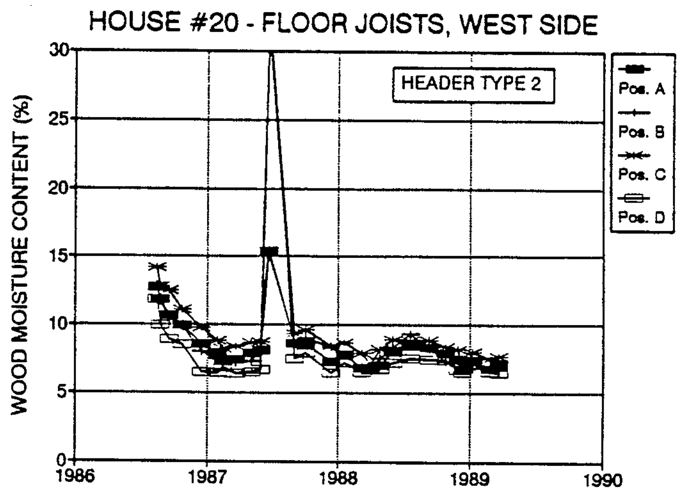


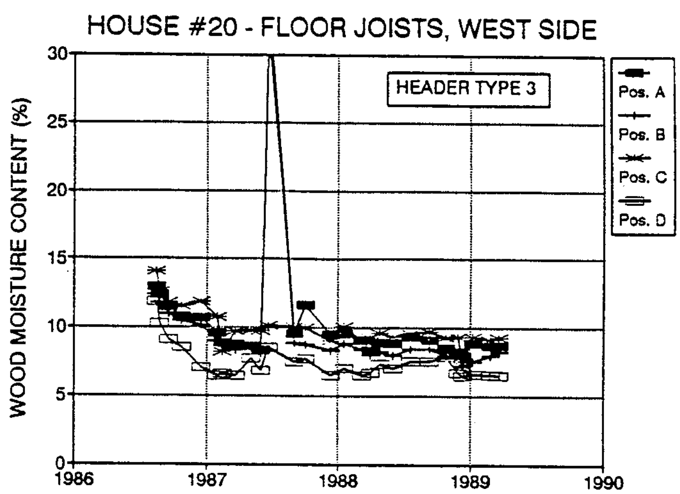
HOUSE #20 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 3
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

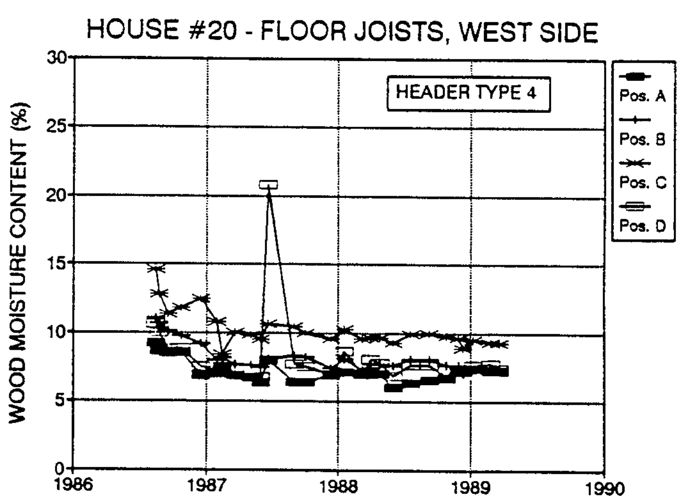

HOUSE #20 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 4
WOOD MOISTURE CONTENT (%)
Pos. A
Pos. B
Pos. C
Pos. D
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

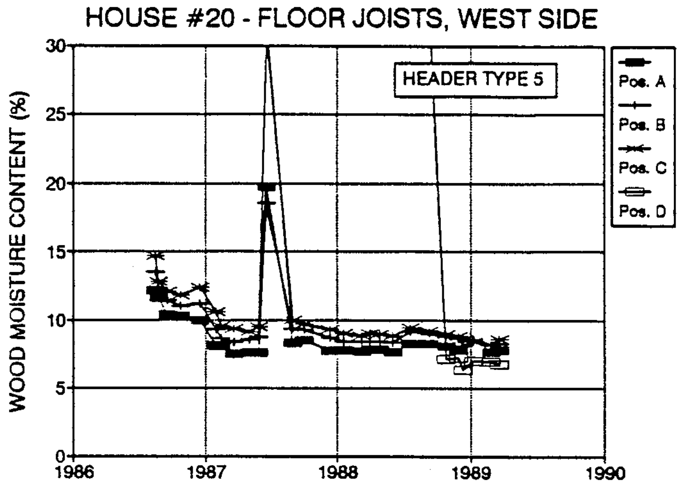

HOUSE #20 - FLOOR JOISTS, EAST SIDE
HEADER TYPE 5
WOOD MOISTURE CONTENT (%)
Pos. A
Pos. B
Pos. C
Pos. D
0
5
10
15
20
25
30
1986
1987
1988
1989
1990


HOUSE #20 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 1
WOOD MOISTURE CONTENT (%)
Pos. A
Pos. B
Pos. C
Pos. D
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

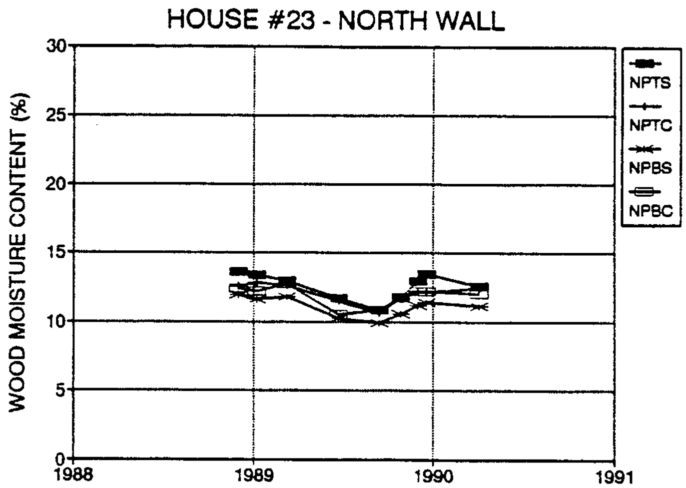

HOUSE #20 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 2
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

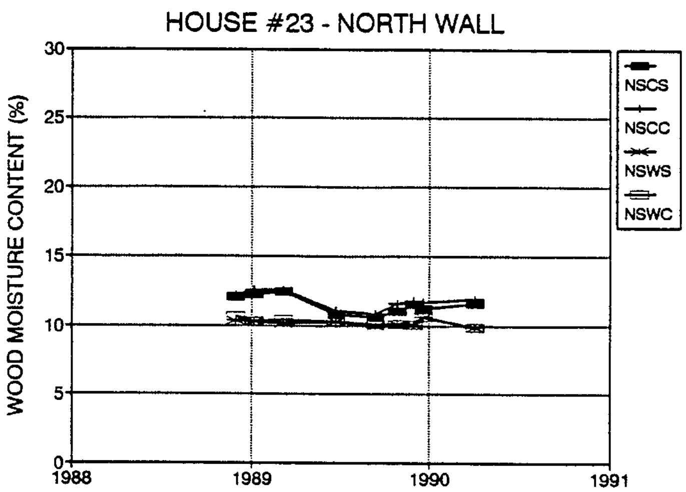

HOUSE #20 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 3
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

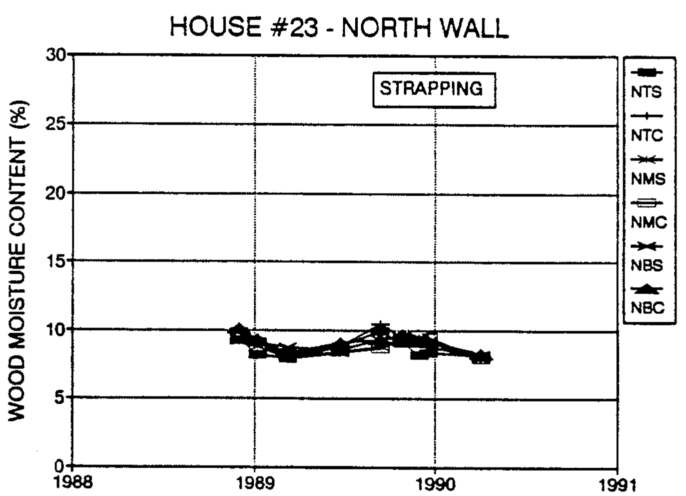

HOUSE #20 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 4
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1986
1987
1988
1989
1990
Pos. A
Pos. B
Pos. C
Pos. D

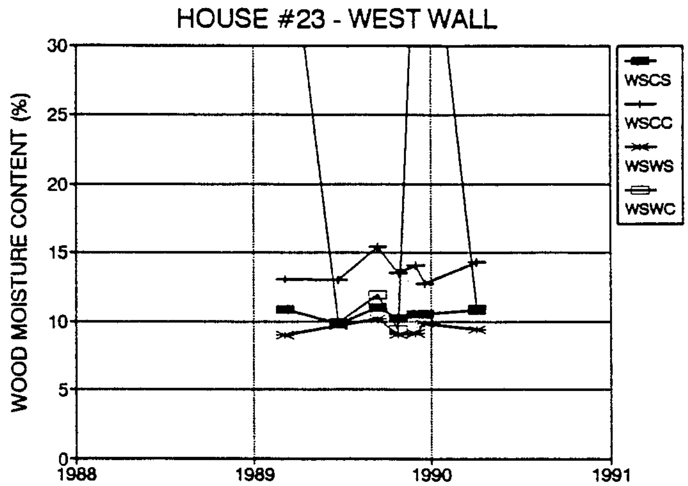


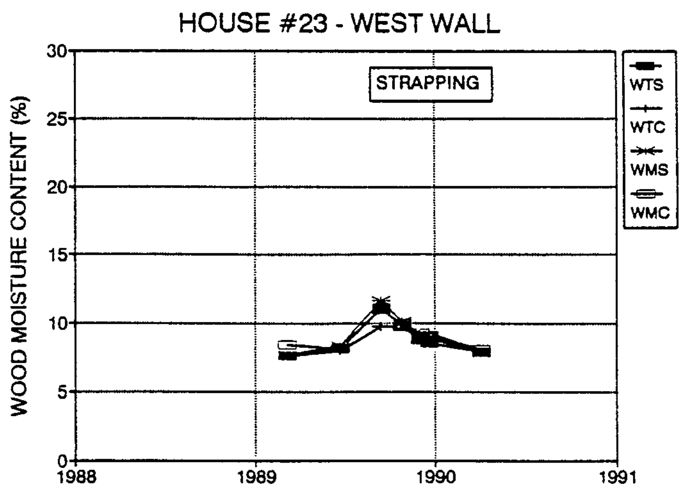
HOUSE #20 - FLOOR JOISTS, WEST SIDE
HEADER TYPE 5
Pos. A
Pos. B
Pos. C
Pos. D
WOOD MOISTURE CONTENT (%)
0
5
10
15
20
25
30
1986
1987
1988
1989
1990

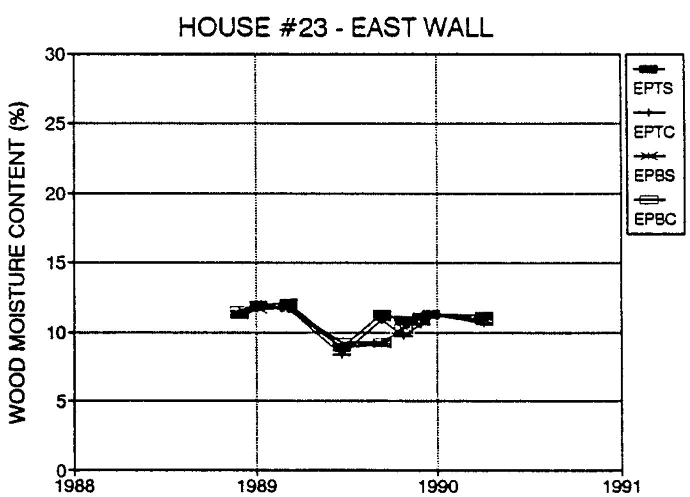

HOUSE #23 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
NPTS
NPTC
NPBS
NPBC

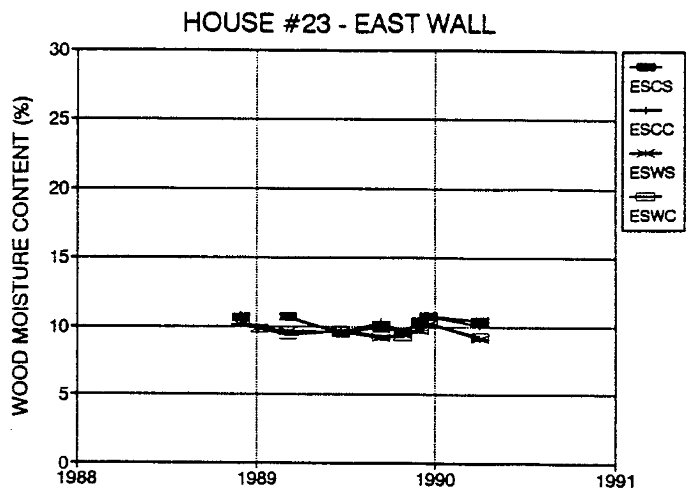

HOUSE #23 - NORTH WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
NSCS
NSCC
NSWS
NSWC

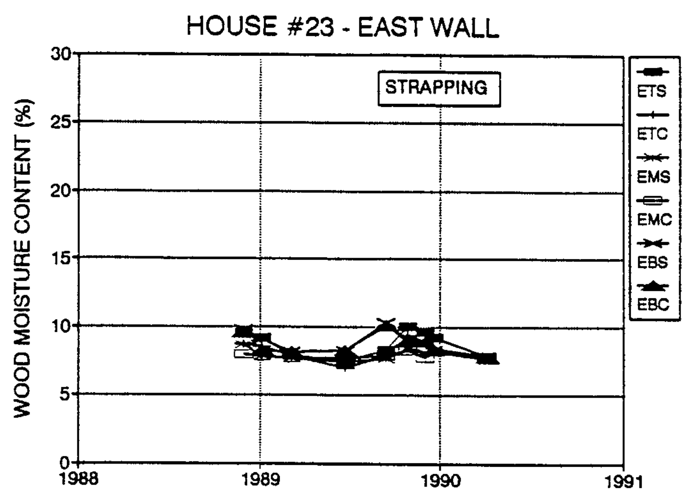

HOUSE #23 - NORTH WALL
STRAPPING
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
NTS
NTC
NMS
NMC
NBS
NBC


HOUSE #23 - WEST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
WSCS
WSCC
WSWS
WSWC


HOUSE #23 - WEST WALL
STRAPPING
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
WTS
WTC
WMS
WMC


HOUSE #23 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
EPTS
EPTC
EPBS
EPBC


HOUSE #23 - EAST WALL
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
ESCS
ESCC
ESWS
ESWC


HOUSE #23 - EAST WALL
STRAPPING
WOOD MOISTURE CONTENT (%)
30
25
20
15
10
5
0
1988
1989
1990
1991
ETS
ETC
EMS
EMC
EBS
EBC