Thermal behaviour of polyurethane foam insulation

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Fraser, H.W. and Jofriet, J.C. 1993. **Thermal behaviour of polyurethane foam insulation**. Can. Agric. Eng. **35**:057-065. Polyurethane foam insulation (PUFI) sprayed on galvanized steel was subjected for 375 days to thermally induced vapour pressure gradients. The 'warm' side of the PUFI was exposed to a temperature of $25^{\circ}C$ and 90% relative humidity, while the 'cold' steel side temperature was cycled from $-8^{\circ}C$ to $5^{\circ}C$ every 6 hours to simulate freeze/thaw conditions. After 375 days of testing (800 kPa•d of vapour pressure days), the PUFI had absorbed 2.7% water by volume, increasing its overall thermal conductivity from about 24 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$ to 32 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$. This means a loss in thermal resistance of about 25%. An asphaltic type vapour barrier was very effective in preventing moisture migration into the PUFI and the embedded wood framing members. Alternative construction techniques require further investigation.

Keywords: polyurethane foam insulation, thermal conductivity, moisture, vapour pressure gradient, freeze, thaw.

La mousse polyuréthanne isolante (MPUI) ayant été vaporisée sur de l'acier inoxydable fut placée sous l'influence d'un gradient de pression vapeur produit thermiquement, pour 375 jours. Le côté chaud de la MPUI fut exposé à une température de $25^{\circ}C$ et à une humidité relative de 90%. A fin de simuler des conditions de gel et dégel, le côté froid fut présenté à des températures variant de $-8^{\circ}C$ à $5^{\circ}C$ selon des cycles réguliers de 6 heures. Après la durée de 375 jours (800 kPa•j de pression vapeur), la MPUI avait absorbé 2.7% d'eau par unité de volume, augmentant sa conductivité thermique de 24 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$ à 32 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$. Ceci indiquerait une perte de résistance thermique d'à peu près 25%. L'écran à vapeur de type asphaltique fut très efficace pour empêcher la pénétration de l'eau dans la MPUI et sa charpente de bois. On recommenderait que ces techniques soient enquêtées d'avantages en tant qu'alternatives de construction.

Mots Clés: Mousse polyuréthanne isolante, conductivité thermique, gradient pression vapeur, gel, dégel

INTRODUCTION

Over the past 15 to 20 years, polyurethane foam insulation (PUFI) has become the insulation of choice for many agricultural structures because it:

- has a low thermal conductivity (about 24 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$);
- is easy to apply in awkward locations, and on irregular surfaces;
- provides an airtight seal, reducing convective heat losses or gains; and
- increases somewhat the rigidity of the building.

In many agricultural buildings, significant differences in temperatures and vapour pressures exist between inside and outside faces of the walls. Designers, builders, and farmers have protected the wall insulation against moisture penetration by installing polyethylene vapour barriers on the 'warm' side of the wall. However, many people made the incorrect assumption that PUFI itself forms an effective vapour barrier and a separate vapour barrier is almost never employed.

The first reported problems caused by water migrating into PUFI were in the early 1980's in potato storages in Quebec and Ontario (Munroe et al. 1985). These wood frame buildings, clad from the outside with galvanized sheet steel, had PUFI sprayed onto the steel cladding from the inside of the building and over the wood studs, girts, and bottom plates. Munroe et al. (1985) reported moderate to severe wood rotting, especially at the base of the walls, and in some cases structural collapse under the lateral pressure of the potatoes.

The problem of rotting of the lower portion of studs, girts and plates, and the reduced effectiveness of wet PUFI prompted the project of which this study is part. The objectives of this study were to determine the combined effect of a vapour pressure gradient, time, freeze/thaw cycling, gravity, presence of vapour barrier, and embedment of wood framing members, on moisture migration into PUFI, and the resulting loss of effectiveness as an insulating material.

LITERATURE REVIEW

PUFI is commonly produced from the reaction of two main components, a polyhydroxyl and a polyisocyanate and a catalyst to control the speed of the reaction. The blowing agent is normally a fluorocarbon refrigerant such as CCl_3F (Freon-11). A surface-active agent is used to control the surface chemistry of the process (Shirtliffe 1978; Blaga 1974; Suh and Skochdopole 1987; BASF Canada Inç. 1986). The reaction of the two main ingredients produces heat which expands the CCl_3F and forms closed cells.

The low thermal conductivity (about 8.4 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$) blowing agents, like Freon-11, contained in the cells give PUFI a low thermal conductivity (about 24 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$) This compares well to other agricultural building insulations like fibreglass batts which have a thermal conductivity of about 41 $mW{\bullet}m^{-1}{\bullet}^{\circ}C^{-1}$. The insulation thickness has an effect on the vapour pressure gradient. That is, from Fick's law (ASHRAE 1985);

$$w = \mu(dp/dx) \tag{1}$$

where:

w = mass of vapour diffusing through unit area in unit time,

p = vapour pressure,
x = distance along the flow path,
μ = permeability, and
dp/dx = vapour pressure gradient.

Obviously, the thinner the insulation, the greater is dp/dx, and the greater is the diffusion of water vapour into the PUFI.

There are annoying differences in the literature in the units used to report the amount of water that has migrated into insulation during experiments or field tests. There are four methods used: g water/cm^3 of PUFI; percent water by weight (wet PUFI basis); percent water by weight (dry PUFI basis); percent water by volume of PUFI. The last method involves the volume of water compared to the volume of PUFI. The advantages of this method are that the volume of PUFI does not change with water addition, the relationship between the volume of added water and the percentage water by volume is linear, and the PUFI density is absent in the ratio allowing comparison of different foams. The present study reports moisture contents using the percent water by volume method.

There have been only five controlled laboratory tests involving a thermally induced vapour pressure gradient between the 'warm' and 'cold' sides of the PUFI, combined with a vapour barrier at the 'cold' side. All of the tests used different environmental conditions, PUFI thicknesses, and days of testing, so that comparison of the results is difficult.

A method that allows some comparison between experiments is to calculate for each test the number of vapour pressure gradient days (kPa•d/mm) to which the test specimens were subjected. This measure is the difference in vapour pressure (kPa) across the thickness of the PUFI sample at any given time divided by the PUFI thickness (mm) multiplied by the period (days) over which this vapour pressure gradient occurred. Table I summarizes previous test results and shows the calculated number of vapour pressure gradient days (kPa•d/mm).

Levy's (1966) tests showed that moisture entered the 'warm' side of the PUFI, then condensed and turned to ice at a 'freeze-line'. His experiment was the only one (prior to the present study) with freezing temperatures on the cold side of the insulation. In his work, the outside temperature was constant. Figure 1 shows Levy's percent water by volume versus position measured from the cold face of the PUFI. The water concentration was highest on the cold side of the insulation, where the water moving from the warm to the cold side was stopped by the steel.

Tobiasson et al. (1987) stated that cellular plastic insulations such as PUFI would wet much faster by subjecting them to thermally induced vapour pressure gradients, rather than by water immersion. Schwartz et al. (1989) found that the water permeance of PUFI was independent of temperature between 10°C and 21.5°C, but increased dramatically with temperatures above 21.5°C.

House (1990) simulated the environment of a very warm and humid swine barn inside a 1 m^3 test box. The outside of the box was kept constant at 5°C. After a period of 128 days of testing, House was unable to detect moisture in the PUFI. The vapour pressure gradient was far less than in previous research experiments; thus, the experiment may not have run long enough to get wetted PUFI results.

Several authors (Levy 1966; Paljak 1973; Schwartz et al. 1989; Tobiasson et al. 1987) have shown that water vapour can enter PUFI under thermally induced vapour pressure gradients. This resulted in an increase in the thermal conductivity of the PUFI by replacing the low thermal conductivity gases in the cells with water. Three researchers reported the thermal conductivity at various moisture contents (Levy 1966; Paljak 1973; Tobiasson et al. 1987).

Levy (1966) developed a formula for the increased thermal conductivity of PUFI based upon its volumetric gain of water (converted to SI units):

$$k = 17.3 + 1.9M \qquad (2)$$

where:
k = thermal conductivity (mW•m^{-1}•°C^{-1}), and
M = water content (% by volume).

Levy's formula was only valid for water gains up to about 10% by volume. The dry thermal conductivity of 17.3 mW•m^{-1}•°C^{-1} for fresh PUFI could be considered quite low. Paljak (1973) observed a non-linear relationship between moisture content and thermal conductivity. He tested PUFI under an extremely high vapour pressure difference (27.8 kPa), using warm side temperatures of 68°C. Tobiasson et al. (1987) related the thermal conductivities of wet and dry PUFI by a ratio and called this the 'Thermal Resistance Ratio'

Table I. Moisture migration experiments with vapour pressure gradients in the PUFI and a vapour barrier at the 'cold' side

Reference	T_i °C	T_o °C	VP kPa	Time days	Thick mm	VPGD kPa•d/mm	% Water by Volume
Levy (1966)	37.8	-28.9	6.5	560	102	35.7	9.4
Paljak (1973)	68.0	4.0	27.8	148	50	82.3	28.8
Tobiasson et al. (1987)	29.0	4.4	3.5	400	25	56.0	45.0
Schwartz et al. (1989)	50.0	5.0	11.5	64	25	29.4	36.7
House (1990)	20.0	5.0	1.35	86	60-80	3.5	NA

T_i = warm side temperature; T_o = cold side temperature; VP = difference in vapour pressure across test sample;
Time = duration of experiment; Thick = thickness of sample; VPGD = vapour pressure gradient days; NA = no detected moisture.

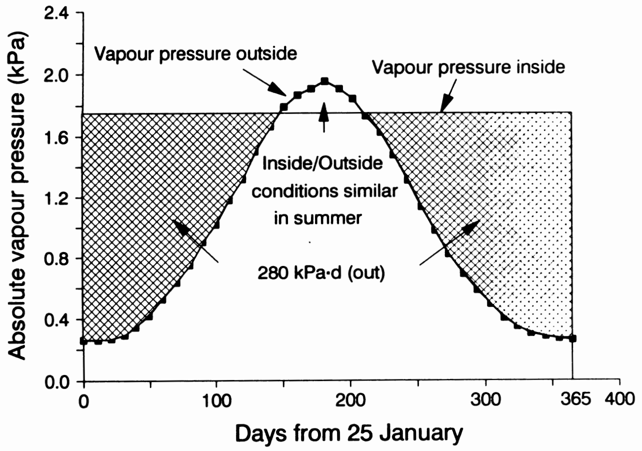

Fig. 1. Water accumulated in PUFI in Levy's (1966) test; water content in % by volume versus distance measured from cold side.

(TRR). It was defined as the ratio of wet to dry thermal resistance of PUFI. This was thought to be a good method of giving the thermal efficiency of wet insulations.

There are no published experiments with PUFI exposed to a combined vapour pressure gradient and freeze/thaw cycling. Freezing and thawing alone does not cause damage to the insulation. However, if preceded by the entry of moisture, damage to the cell structure may occur.

Levy (1966) noted that ice formation in PUFI is a serious concern, since ice has a thermal conductivity one hundred times greater than the PUFI or water vapour. Shirtliffe (1978) stated that wet PUFI subjected to freeze/thaw cycling could disintegrate after a few dozen cycles. Jackson (1974) noted that water vapour deposits itself in the cells as discrete droplets, discontinuous from each other, or as a continuous film. When the discrete droplets freeze, the volume change occurs without any effect on the cell walls. However, when a continuous film of water freezes onto a cell wall, the change in dimension could cause rupture of the wall material.

AGRICULTURAL CONSTRUCTION AND CONDITIONS

Farm buildings represent the majority of work for many of the up to 50 Ontario contractors who install PUFI (Private communication with Kast, Canadian Urethane Foam Contractors Association, Toronto, ON). PUFI has been used almost exclusively in the horticultural storage industry since the early 1970's. It has been most popular in both new and renovated swine buildings and used to a lesser extent in other livestock facilities. It is estimated that at least 50% of the Ontario horticultural storages, and up to 15% of the swine barns contain PUFI (Personal communications: C. Strassburger, President, Canadian Urethane Foam Contractors Association, Kitchener, ON; F. Kains, Ontario Ministry of Agriculture and Food Engineering Swine Specialist, Guelph, ON; Potato Growers Marketing Board, Burlington, ON; J. Uyenaka, Ontario Ministry of Agriculture and Food, Horticultural Specialist, Ancaster, ON) (Fraser 1989; OMAF 1988).

When PUFI was first used on agricultural buildings, the construction method consisted of building the timber frame, installing the outside steel cladding directly on the studs, or on horizontal girts, followed by the application of PUFI on the steel cladding from the inside of the building. The girts allowed the PUFI to 'wrap around' the studs, get between the steel and the studs, and thus reduced the area for thermal bridging through the studs. The above method of construction was the quickest and cheapest. It also had a number of disadvantages, including the need for a fire protective coating, the possibility of mechanical damage during use, and a surface that was hard to clean.

In addition to the disadvantages, there were reports of rotting studs, plates, and girts in some potato storages in Quebec and Ontario (Munroe et al. 1985). It was thought that stud encapsulation by the PUFI might not allow the timber to 'breathe', or that studs were already wet during construction.

Environmental conditions and vapour pressure gradients across the insulated shell of agricultural structures vary depending on their use and time of year. In most farm buildings, insulation thicknesses range from 50 to 100 mm.

Figures 2, 3, and 4 have plots of the vapour pressure differences using the average outside vapour pressure data for Elora, ON for three different agricultural interior conditions including a finishing hog barn, a table potato storage, and a summer refrigerated storage. The areas between the curves represent the number of kPa•d of vapour pressure difference across the wall or ceiling. These figures can be divided by the insulation thickness to give the vapour pressure gradient days.

For the hog finishing barn (Fig. 2), the vapour pressure inside is almost always higher than outside, and the area between curves for this condition is about 280 kPa•d. However, there have been no published reports of problems with PUFI in swine barns.

For a table potato storage (Fig. 3), the vapour pressure is sometimes greater outside, at other times inside. This causes a reversal of direction of flow. In this case the total vapour pressure gradient days causing migration of moisture from

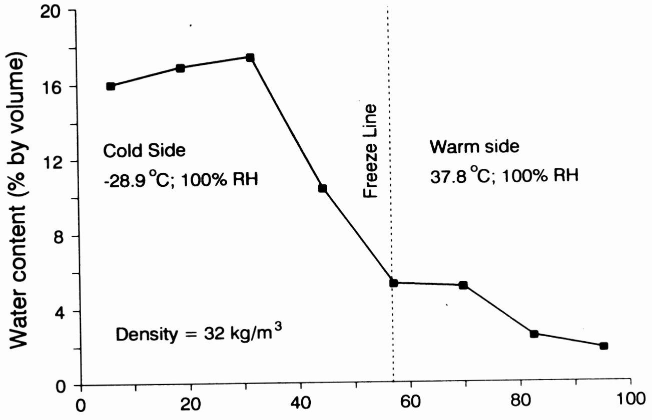

Fig. 2 Typical vapour pressures (kPa) inside a finishing hog barn and outside (Elora, ON), versus time of year (interior temperature 20°C and 75% RH).

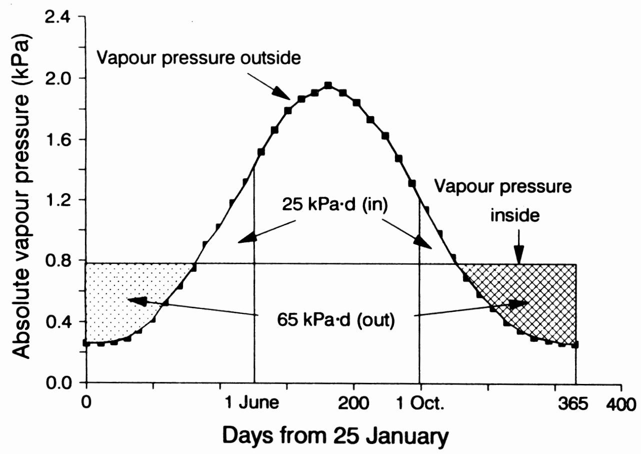

Fig. 3. **Typical vapour pressures (kPa) inside a table potato storage building and outside (Elora, ON), versus time of year (interior temperature 5°C and 90% RH).**

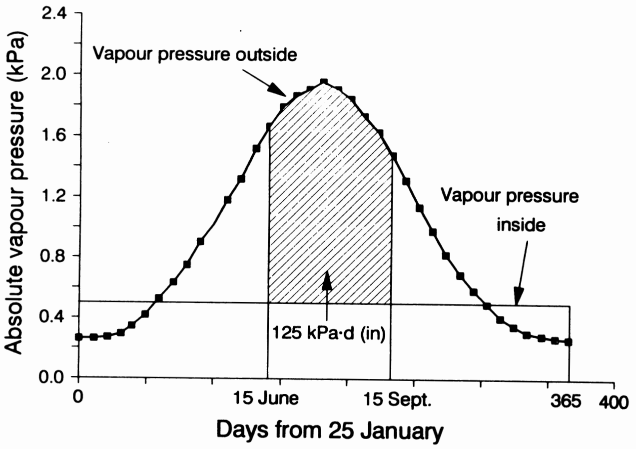

Fig. 4. **Typical vapour pressures (kPa) inside a refrigerated horticultural storage building and outside (Elora, ON), versus time of year (interior temperature 0°C and 90% RH).**

inside to outside are 65 kPa•d, and from outside to inside of 25 kPa•d. It is mainly potato storages where moisture in PUFI has been identified as a problem.

For a summer refrigerated storage for horticultural crops, the vapour pressure gradient always causes moisture migration from outside to inside at about 125 kPa•d (Fig. 4). There have been no published reports of problems with PUFI in these storages.

Table II shows inside building conditions, and the resulting kPa•d of vapour pressure, and calculated kPa•d/mm of vapour pressure gradient for several agricultural uses and typical insulation thicknesses. The direction of this gradient is indicated as 'out' (causing vapour to migrate out of the building), and as 'in' for the reverse. It is obvious that there are uses with vapour pressure gradients in both directions. This problem occurs in horticultural buildings which are used in both winter as a 'heated' storage, and in summer as a 'refrigerated' one. These types of storages are more likely to occur in the future, as farmers attempt to prolong marketing seasons and utilize these expensive storages for other purposes in order to increase the number of days per year that they are in use.

The combination of cycling winter freezing and thawing temperatures in Ontario can cause damage to building materials that contain water. Moisture in a closed cell material like PUFI could be a problem under these conditions.

In Ontario, the two months when freeze/thaw conditions occur regularly are March and December. If it is assumed that one freeze/thaw cycling day occurs for every day when the high is 0°C or above and the low is 0°C or below, an estimate can be made of the number of freeze/thaw cycling days there are in a year. For Elora this is from about February 23 to April 3, and from November 23 to December 31, a total of 77 days. The yearly number of freeze/thaw cycling days will vary from location to location, but likely 75 days per year is a conservative estimate for most locations in Southern Ontario. South and west facing walls probably have more cycles because solar radiation would raise the walls' outside temperature to above 0oC on clear days that had ambient highs below 0°C.

The penetration depth of freezing temperatures into insulation is greatest in horticultural storages, because they generally have thicker insulation and lower interior temperatures than livestock barns. Table III shows the penetration of freezing temperatures for three building uses and two insula-

Table II. Typical environmental conditions, use periods, and calculated exposure in Ontario agricultural structures

Use	°C	%RH	kPa	Use period	kPa•d Out	kPa•d In	kPa•d/mm Out	kPa•d/mm In
Weaner Pigs	24	75	2.24	All year	440	-	5.9	-
Finish Hogs	20	75	1.75	All year	280	-	5.6	-
Chip Potato	12	90	1.26	1/10-1/6	165	-	1.6	-
Table Potato	5	90	0.79	1/10-1/6	65	25	0.9	0.3
Squash	10	65	0.80	15/10-15/4	70	-	0.7	-
CA Apples	0	90	0.55	1/10-1/5	30	20	0.4	0.3
Onions	0	60	0.37	15/10-1/5	10	30	0.1	0.4
Summer F/V	0	90	0.55	15/6-15/9	-	125	-	1.7

Table III. Penetration depth of freezing into PUFI from outside to inside (mm), assuming outside temperatures of -10°C

Use	Inside Temp.(0°C)	50 mm PUFI	75 mm PUFI
Finishing Hogs	20	17	25
Table Potatoes	5	33	50
Refrigerated Storage	[a]0	50	75

[a] Storages refrigerated in summer but not used in winter usually have inside temperatures above freezing even during an Ontario winter.

tion thicknesses. For potato storages with 75 mm of insulation, the penetration of freezing temperatures is quite deep compared with a swine barn with only 50 mm of PUFI.

LABORATORY TESTS

A model barn, heating and humidity equipment, environmental chamber, as well as recording equipment described by House (1990), with minor modifications, was used for the laboratory tests. The model barn had five 1 m x 1 m removable test panels, two for temperature profile measurement inside the PUFI (panels A and B), two for sample removal (panels C and D), and one ceiling panel to test the effect of using a vapour barrier coating during construction (panel E). Each of the five test panels was sprayed with 50 mm (nominal) layer of PUFI on the inside. The actual thickness of the samples cut from panels C and D ranged from 50 to 60 mm. Local extremes of 75 mm occurred at the embedded thermocouples in panels A and B. Figure 5 shows the arrangement of test panels.

The gamma-spectrometer used by House (1990) was used for measuring moisture in PUFI. This instrument uses gamma spectroscopy, the interaction of electromagnetic radiation and matter, to determine both the location and magnitude of water in the PUFI. The greater the amount of water present in PUFI, the more radiation is absorbed. The gamma spectrometer was calibrated to give moisture contents in wet PUFI by comparing radiation absorption to that in the same location in the dry PUFI sample (Jiang et al. 1989).

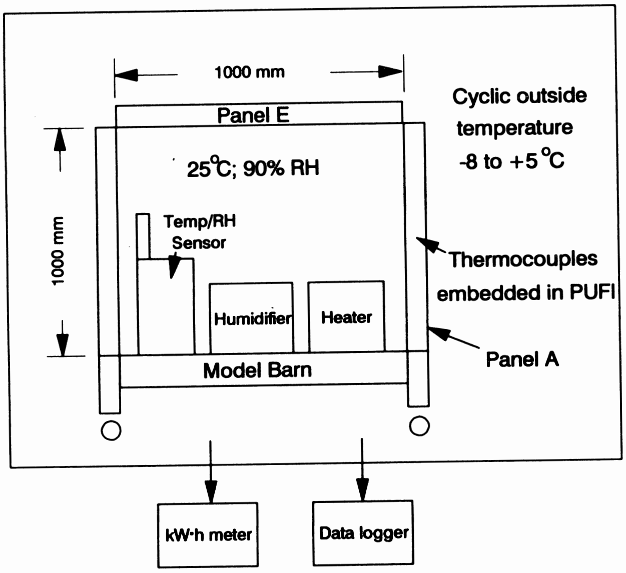

Fig. 5. Vertical cross section of the model barn experimental setup inside the environmental chamber.

Vertical wall panels A and B

The function of wall panels A and B was to record temperature profiles through the thickness of the PUFI. Ten thermocouples were used in both panels to record this profile, two in close contact with the faces of the panels and eight encapsulated in the PUFI at 2.5, 7.5, 12.5, 17.5, 22.5, 27.5, 32.5 and 37.5 mm from the cold side. A modified glass tubing apparatus (House 1990) was used to hold the thermocouples buried in place within the PUFI during its expansion and curing period. As well, the ambient temperatures inside and outside the model barn and the interior humidity were recorded. All temperatures and the humidity in the model barn were measured every minute, then averaged over a 30 minute period and recorded.

Vertical wall panels C and D

Panels C and D were prepared for sampling according to the layout shown in Fig. 6. The galvanized metal "siding" was painted only outside the 16 sample areas (100 mm long by 50 mm wide) to improve adherence of the PUFI to the steel. The layout on each panel was designed to determine whether there were any gravitational effects on the infiltration of water. The 50x100 mm samples were cut from the insulation with a knife and removed with a specially designed lifting tool. The opening in the insulation was immediately filled with a spare piece of PUFI and sealed with silicone sealant.

House (1990) had noted warping of some PUFI samples due to drying in an oven at about 50°C. In this experiment samples were dried in a refrigerator at about 4°C. Sample masses were checked periodically (to the nearest 0.1 g) during the drying period. When there was no further decrease in their masses, samples were considered to be dry.

Horizontal ceiling panel E

A vapour barrier coating was tested on ceiling panel E. More importantly, this panel was designed to test if wood studs had any wicking effect on PUFI. Thus, some timber members were incorporated in the construction.

Panel E was divided into four sections, each about 0.5 m square, separated by acrylic plastic strips over the full depth of the PUFI. Spruce studs (38 mm x 56 mm) were attached to the galvanized steel using screws. The panel was then sprayed with PUFI.

The panel was painted with a black 'Bakelite' asphaltic vapour barrier coating, about 0.5 mm thick, as shown in Fig. 7. The northwest quadrant with no vapour barrier was similar

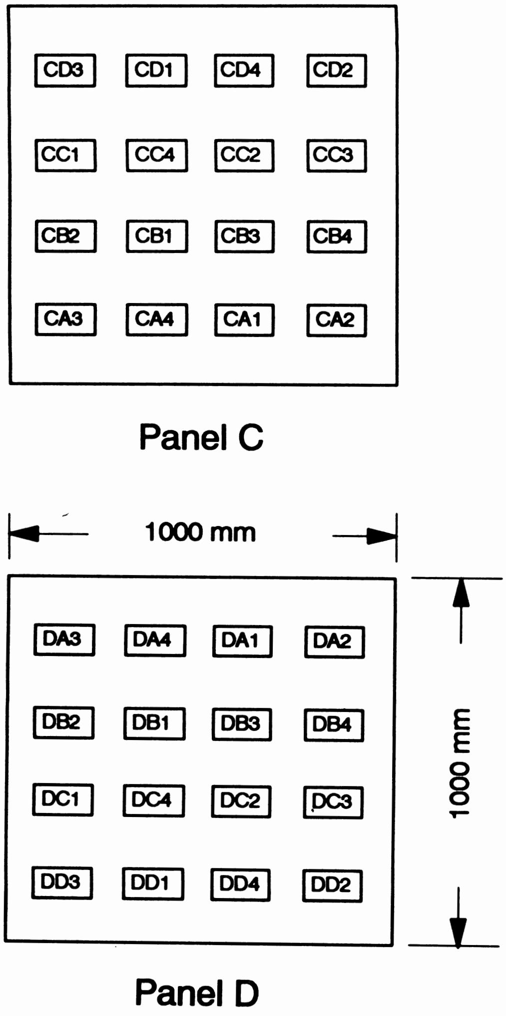

Fig. 6. Sample layout on vertical panels C and D; elevation of panels from the inside of the model barn.

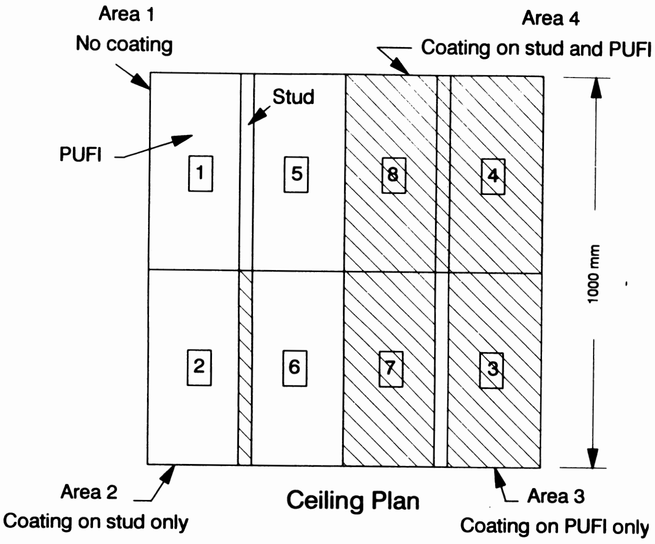

Fig. 7. Layout of ceiling panel E.

to the exposure conditions of panels A, B, C, and D; the southwest and southeast quadrants were intended to determine if the studs were wicking water. In the northeast quadrant the timber and PUFI were both coated to determine the effects of this treatment. The moisture content of the spruce studs was measured on the side exposed to the model barn environment with a wood moisture meter (Delmhorst Instrument Company, Model G-30).

Environmental conditions inside and outside model barn

To test the possible effects of freezing and thawing, temperatures were cycled on the outside or 'cold' side of the model barn, from -8°C to 5°C, four times daily. Because the environmental chamber experienced some difficulty in consistently producing freezing temperatures, the total length of time below 0° was set at about 4 hours out of each 6 hour cycle, a total of 16 hours per day. The inside of the model barn was kept at 20°C until day 65, at 23°C until day 90, and then at 25°C until the end of the test.

The relative humidity inside the model barn was kept at 90%. Because of the cycling outside temperatures, the vapour pressure difference across the shell of the model barn varied with time. The vapour pressure gradient days were calculated from the observed temperatures inside and outside the model barn and from the observed interior relative humidity. The maximum was about 2.4 kPa•d over a one day period.

The electrical energy input necessary for running the humidifier, heater fan, and heater to maintain the interior model barn temperature was recorded. Changes in energy input were assumed to be related to a change in thermal conductivity of the PUFI.

RESULTS AND DISCUSSION

The experiment ran 375 days. There were some equipment difficulties during the summer months; the environmental chamber was not able to cool down to the set temperature on very hot days. Little water entered the PUFI initially, but sometime around day 190, after 400 kPa•d of vapour pressure difference across the model barn panels, a distinct change in freezing temperature penetration showed that water was starting to accumulate.

Analysis of vertical wall panels A and B

Figure 8 presents for days 10, 152, and 365 measured temperatures outside panel A and five temperatures inside the PUFI at 2.5, 7.5, 12.5, 17.5, and 22.5 mm from the cold, steel side of panel A. For day 10 (15 kPa•d of vapour pressure difference accumulated from the start of the test), the PUFI temperatures 'followed' the outside temperature profile, with a lag period of about 0.5 to 1.0 hour. The PUFI temperatures 22.5 mm away from the cold, steel side dipped below freezing when outside temperatures were about -8°C. The curves were more or less equidistant indicating that the temperature profile through the thickness of the insulation was linear. The PUFI was still dry.

By day 152 (310 kPa•d), the inside temperature of the model barn had been increased to 25°C, resulting in higher PUFI temperatures at 22.5 mm depth compared to day 10 (Fig. 8). There was little change in the time lag on day 152, and the temperature profiles were still equidistant. However,

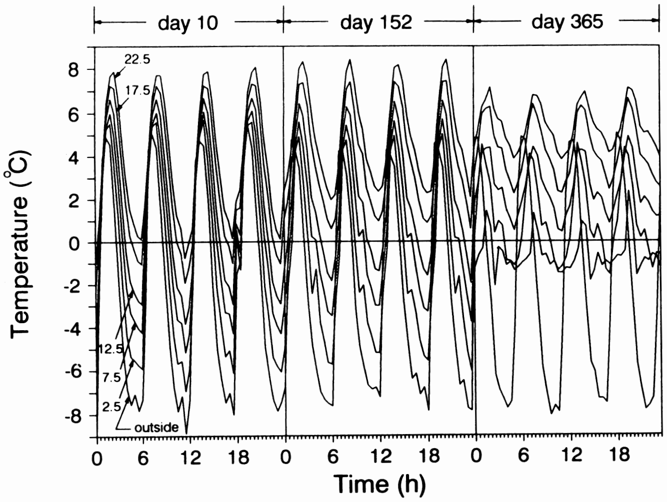

Fig. 8. Temperature versus time on days 10, 152, and 365; outside temperature and those inside the PUFI 2.5, 7.5, 12.5, 17.5, and 22.5 mm from the cold (outside) face.

because of the increased temperature in the model barn, depth of penetration of freezing temperatures in the PUFI was less than on day 10. It was concluded that at the location of the thermocouples, the PUFI was still relatively dry.

Figure 8 shows clearly the increase in time lag and the change in the temperature profile on day 365. Note that when the outside temperature was at about -8°C at hour 4, the PUFI temperature did not reduce to the same value as it had previously when the PUFI was dry. Note also that as the outside temperature rose to about 5°C at hour 6 on day 365, that the PUFI temperatures did not increase correspondingly as they had on days 10 and 152. Freezing temperatures did not penetrate to the same depth as on day 152. It is apparent that by day 365 (780 kPa•d) considerable water had penetrated into the PUFI and that the presence of water was damping the temperature fluctuations in the PUFI.

Penetration of below 0°C temperatures

The thermocouples embedded in the PUFI registered over 100,000 temperatures throughout the experiment. The data were scanned to count how many times the temperatures dipped below 0°C at each thermocouple location. The results are shown in Table IV for the period before and after moisture accumulation became apparent on day 190 (380 kPa•d).

Apparently, the penetration of freezing temperatures was reduced considerably with the onset of moisture migration, due to the relatively quick temperature cycling, the high specific heat of water, and the heat of fusion of water and ice. Freeze/thaw cycling did not affect PUFI before the onset of moisture. However, the depth of moisture accumulation (about 14 to 18 mm as shown later) may have caused accelerated freezing damage.

Analysis of vertical wall panels C and D

After 330 days of testing (690 kPa•d), three samples from panel D were removed for moisture analysis. Later, after 364 days of testing (775 kPa•d), three samples were removed from panel C and tested. Wet samples of PUFI were analyzed by gamma-spectrometry at the end of the experiment, then dried thoroughly in a refrigerator for about 35 days, and reanalysed in the gamma-spectrometer at the same locations. An attempt was made to take samples vertically 'in-line' with each other on the panels to see if there were gravitational effects.

Figure 9 shows the percent water by volume versus depth through the PUFI for the three D panel samples. One moisture profile was completed down the centre of each sample. Because the gamma ray spectrometer had a small error of 2 to 3% in its readings, moisture contents below about 2% by volume could not be determined using this method.

Samples from panel D absorbed more water than those on panel C, likely because of the smaller thickness of the D

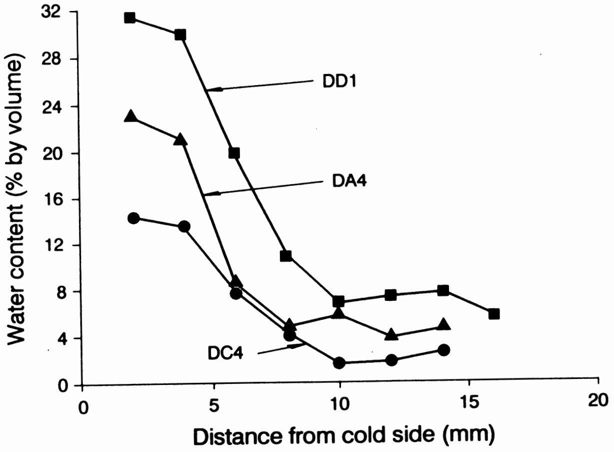

Fig. 9. Water content versus distance from the cold (outside) face for three samples from panel D.

Table IV. Number of times that temperatures dropped below freezing over the duration of the experiment on panels A and B

		Thermocouple depth (mm)				
Period	Outside panel	2.5	7.5	12.5	17.5	22.5
Panel A, Before Day 190	812	771	851	763	417	121
Panel A, After Day 190	563	456	447	48	5	0
Panel B, Before Day 190	817	766	853	775	651	231
Panel B, After Day 190	568	488	448	178	50	6

Table V. Vapour pressure gradient days (VPGD) for panels C and D samples

Sample	kPa•d	Thickness (mm)	VPGD	% by Volume
DD1	690	44	15.7	5.4
DC4	690	50	13.8	2.4
DA4	690	48	14.4	3.2
CA2	775	58	13.4	1.4
CB4	775	58	13.4	1.7
CC3	775	56	13.8	1.9

samples and the subsequent steeper vapour pressure gradient. There was no evidence of gravity effects. All six samples exhibited the same moisture profile shape and location. The moisture content was always highest on the 'cold' steel side of the PUFI, where the moisture was trapped by the steel vapour barrier. The moisture profiles were consistent with those found by Levy (1966) and other researchers. Measurable amounts of moisture were found in the cold part of the insulation nearest the siding to about 14-18 mm from the steel or about 30% of the total PUFI thickness.

When the samples were removed, it was not apparent visually or physically that moisture was present. However, a shift of the centre of gravity to the cold side from that of the dry PUFI samples (found by suspending the samples from a fine thread) was measurable confirming the moisture gradients obtained with the gamma ray spectrometer.

To obtain an overall moisture content, the samples were weighed both wet and dry and their volumes were determined by measuring water displaced when immersed. Their moisture contents were then determined from the overall densities. All values are summarized in Table V together with calculated values for the vapour pressure gradient days discussed earlier.

The insulation was not subjected to the high vapour pressure gradient days found in most previous research experiments (see Table I). A plot of percent water by volume versus vapour pressure gradient days for these samples is shown in Fig. 10. Although there were too few samples, there was some indication that the higher the number of vapour pressure gradient days the higher the accumulation of moisture.

Analysis of horizontal ceiling panel E

The moisture content of the studs before the experiment was 10% by mass. After 375 days in the experiment, the exposed studs had gained considerable amounts of water. The measured moisture content was between 15% and 30% moisture by mass. However, the studs covered by the vapour barrier paint were still as dry as they had been at the beginning of the test.

The ends of the unprotected studs closest to the perimeter of the panel were visibly wetter than the centre portion. This was likely because the studs were coldest there from thermal bridging to the outside cold environment. It did not appear that the PUFI caused any wetting of the studs.

When the samples from panel E were analyzed using the gamma ray spectrometer (Fraser 1991), the results indicated the effectiveness of the vapour barrier coating in keeping moisture out of the PUFI and the timber. Samples with the vapour barrier had no detectable amount of moisture, but those without did. Similar amounts of moisture entered the PUFI samples in ceiling panel E compared to the wall panels C and D. The same characteristic build up of moisture near the 'cold' steel side was evident. However, on ceiling panel E, the moisture profile appeared to be more spread out over a greater portion of the thickness. Moisture could be detected over about 45% of the thickness in ceiling panel E compared to about 30% in the vertical wall panels C and D. This might have been caused by gravity, as the cold, steel side was on the top of the panel. Gravity, therefore acted opposite to the flow direction.

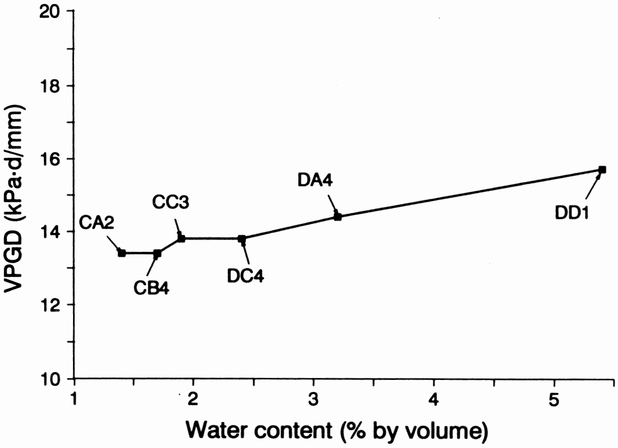

Fig.10. Vapour pressure gradient days (VPGD) versus water content of six samples (three from panel C and three from D).

Analysis of electrical energy consumption

Because the temperature both inside and outside of the model barn varied with time, the energy use information was normalized by dividing it by the temperature difference between the in- and outside of the model barn. Figure 11 shows the relationship between this normalized energy use, W/°C, and the kPa•d of vapour pressure difference across panel A. There was an obvious trend of increased energy use over the duration of the experiment, from 8.75 W/°C to 9.35 W/°C, an increase of 0.6 W/°C. This represents an increase in energy use of about 6.8% over the duration of the experiment. Almost the entire increase must be attributed to either aging or migration of water into the PUFI. It was calculated that the heat loss through the exposed PUFI was 1.72 W/°C at the beginning of the test. Thus the heat loss through the PUFI at the end of the test was estimated to be 1.72 + 0.6 = 2.32 W/°C. In this case, the thermal resistance ratio (TRR) was inversely proportional to the energy increase, or TRR = 1.72/2.32 = 0.74. The TRR of 0.74 indicates a loss of insulating effectiveness for the PUFI. The TRR prediction equation by Tobiasson et al. (1987) indicates a value between 0.81 and 0.91, assuming that the panels averaged 2.7% water by volume. If the thermal conductivity of dry PUFI was 24 mW•m^{-1}•°C^{-1} and the thermal resistance ratio was 0.74, then the overall 'wet' thermal conductivity could be estimated to be about 32 mW•m^{-1}•°C^{-1}.

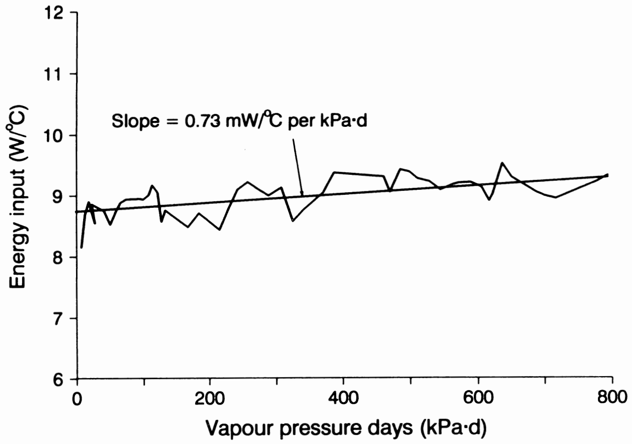

Fig. 11. Measured energy consumption per °C temperature difference between inside and outside face of panel A versus vapour pressure gradient days for the duration of the experiment.

CONCLUSIONS

It can be concluded from this research that moisture will migrate into polyurethane foam insulation (PUFI) and it will adversely affect the overall effectiveness of the PUFI as an insulating material. Further:

- The entry rate of moisture into PUFI is increased by increasing the vapour pressure gradient.
- The amount of moisture entering PUFI is increased by increasing the time exposed to the thermally induced vapour pressure gradient, although under agricultural conditions the effects may take years to become apparent.
- Water contents were found to be always highest at the 'cold', steel side of the PUFI. This is consistent with other researchers' findings.
- There was no evidence of disintegration of the PUFI as a result of freeze/thaw cycling when water was present, as suggested in the literature.
- There was no evidence of gravity causing accumulation of water at the base of the 1 m high experimental vertical wall panels.
- There was no clear evidence to suggest that wood framing members either increased or decreased the moisture content of adjacent PUFI.
- One asphaltic type of vapour barrier coating was very effective in preventing moisture migration into the PUFI and the wood framing members.
- The overall accumulation of moisture in the PUFI was 2.7% by volume and the thermal conductivity of the PUFI increased from an assumed dry value of 24 $\text{mW}\bullet\text{m}^{-1}\bullet{}^{\circ}\text{C}^{-1}$ to a calculated wet value of 32 $\text{mW}\bullet\text{m}^{-1}\bullet{}^{\circ}\text{C}^{-1}$.

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