AN EVALUATION OF THE PERFORMANCE OF A MODIFIED URETHANE FOAM INSULATION

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ABSTRACT

A case study was performed on the use of a modified urethane foam insulation in modular home construction. The technical work was completed by a research center as part of the DOE-sponsored Advanced Housing Technology Program. A national laboratory provided program management and technical support to the project. A 2,800-ft^2 model home was provided to use as a test bed for the installation of both spray-applied (open framing cavity) and liquid-injected (closed framing cavity) applications. An additional liquid test application was made at the national laboratory in collaboration with the Department of Energy's (DOE) Building Materials Program.

The case study consisted of two tasks. The first assessed modified urethane foam's insulating and air-sealing properties against those of the standard practice materials (fiberglass insulation) in the modular home industry. It found the modified urethane foam to be cost-competitive with current practice for installations of comparable performance.

The second task was to determine if the modified urethane foam could be assimilated into a modular home manufacturing process as well as to verify the thermal and air-sealing performance of the product. The open-cavity spray installation of the product went according to plan, offering few problems in a production line environment. Closed-cavity liquid installation caused disruptions when some of the gypsum wallboard deflected from the expanding foam and had to be replaced. The cause of this failure is believed to be associated with the size of the cavity (2-by-6 framing, 24 in. on center) and the high moisture content of the gypsum board in use at the time. During additional testing of the process on smaller cavities (2-by-4, 16 in. on center), no problems with deflection were encountered.

While the project did not find modified urethane foam to be an unqualified success, the project did result in several actions that will help move the product toward its full market potential. These include improved liquid-injection installation procedures that appear to have mitigated the potential of future wall deflection problems and verification of the air-sealing and thermal performance characteristics claimed by the product's manufacturer.

INTRODUCTION

Under the Advanced Housing Technology Program (AHTP) sponsored by the Department of Energy (DOE), a research center is assessing the energy efficiency, cost-effectiveness, and potential for improved performance of innovative, emerging housing technologies. Promising energy-related innovations have been selected as case studies to further apply the evaluation methodology developed as part of the AHTP and to test various strategies for speeding the diffusion of promising energy-saving technologies. The modified urethane foam is an insulation selected for further study because it has the potential to contribute to greater energy efficiency and productivity in the housing industry.

Spray-applied foam insulations are made up of two components that rapidly expand to foam upon mixing. The components are stored in drums and hydraulically delivered in separate lines to a spray gun. The spray gun head is designed to mix and release the components in correct proportion for expansion. The foam expands as it is applied and adheres to framing materials, totally filling the framing cavity with insulation and sealing the building envelope against air leakage. The installers use a box van or container truck to accommodate the pump, drums, and other equipment required for foam application.

The modified urethane foam has a number of unique properties. This insulation has a density ranging from .5 to .7 lb/ft^3, making it considerably less dense than other spray-applied urethane foams. It has a 75% open-cell content, as compared to less than 10% open-cell content of other urethane foams. The modified urethane foam is more pliant than other foams and maintains this pliancy over time. Unlike other urethane foams, this modified urethane foam contains no ozone-depleting chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs)—the blowing agent is water and the cells of the foam are filled with air. The modified urethane foam has no environmentally harmful CFC/HCFC outgassing over time and none of the subsequent shrinkage, loss of R-value,

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and loss of pliancy associated with most other urethane foams. Unlike urea formaldehyde, a froth foam insulation, there are no indoor air quality (IAQ) issues associated with this modified urethane foam.

Since 1982, this modified urethane foam has been applied as a spray foam insulation in open framing cavities. More than 3,000 homes in Canada have been insulated with this insulation and the product has been making inroads in the U.S. insulating market, particularly in the Northeast and Alaska. For the last five years, the manufacturer has been working on a modification to the foam insulation to allow the specialized foam to be liquid injected into closed framing cavities. The development of modified urethane foam's closed-cavity, liquid-injection process is significant for three reasons:

- It eliminates the labor and waste disposal associated with trimming cavity overfill when spray foam is used in open-cavity installations.
- The ability to insulate and air-seal closed cavities makes modified urethane foam well suited for both new construction and retrofit.
- It frees cavity insulation from a specific stage of the construction sequence, providing the opportunity for cycle time reduction.

In addition to the liquid-injected modified urethane foam's potential in new construction and retrofit, there are a number of factors that make the insulation of modular buildings a promising application:

- Modular manufacturers generally already have experience with the equipment necessary to apply modified urethane foam.
- Because modular units must travel over the road, wall insulation is exposed to settling and shifting, and ceiling/floor insulation can be exposed to wind and rain. The pliancy and high adhesion of modified urethane foam to framing materials are well suited to resist these stresses.
- Modular manufacturers also typically use construction adhesives and screw fasteners to secure drywall to framing. The greater holding power of this method of fastening has the potential to streamline the liquid-injection process by reducing the number and size of injection points.

This paper focuses on two of the tasks completed as part of the AHTP modified urethane foam case study:

- *Investigation of Air Infiltration and Vapor Retarder Issues*—The issues of air and vapor movement into and out of building envelopes were investigated as they applied to the properties and asserted benefits of the modified urethane foam insulation.
- *Applications Trial*—Installation of the modified urethane foam insulation in a modular home provided the opportunity to evaluate the workability of the material in the modular construction sequence. Additional observations on the closed-cavity installation process were made at a national laboratory's buildings technology center.

INVESTIGATION OF AIR INFILTRATION AND VAPOR RETARDER ISSUES

The modified urethane foam insulation has properties that may eliminate the need for a separate air infiltration barrier, vapor retarder, and air-sealing techniques. All of these building components or techniques are required or indicated when fiberglass batt insulation is employed. The purpose of the investigation was to determine if the literature, building codes, experts in the field, and computer modeling support this possibility.

The modified urethane foam's functional advantages in comparison to fiberglass batt insulation are its slightly higher R-value, much greater air-sealing capability (lower air permeance[1]), and substantially lower moisture permeance,[2] as presented in Table 1.

Table 1 Comparative Properties of Modified Urethane Foam and Fiberglass[a]

Property	Fiberglass batt	Modified urethane foam
Thermal resistivity (R-value per inch)	3.2 h·ft^2·°F/Btu·in.	3.6 h·ft^2·°F/Btu·in.
Air permeance (for 3 in. of material)	–37 L/s·m^2	1.6 L/s·m^2
Moisture permeance (for 3 in. of material)	> 100 perms	16 perms

[a]The thermal resistivities of both materials are the result of independent ASTM C-518 tests. Modified urethane foam air permeance is from an independent ISSN 0701-5232 standard test. There currently is no ASTM standard test for air permeance, and the approximate permeance is from Energy Design Update 10:8. The moisture permeances of both materials are from ASTM E-96 independent tests.

Standardized laboratory tests are useful in comparing the properties of materials. The actual performance of the insulating material in the building envelope is, however, a function of its ability to maintain the thermal integrity of the interior space over the life of the structure. The ability of a cavity fill insulation to maintain interior thermal integrity is a function of effective R-value (resistance to thermal conduction actually delivered in a framing cavity), resistance to air movement (air permeance), resistance to moisture movement (vapor permeance), and degradation of these parameters over time. No measured data were identified for the installed R-values of modified urethane foam or fiberglass batt insulation. The

[1]The resistance a material provides to the movement of air is called air permeance or permeability. Permeability is actually a rate of air movement measured in cfm/ft^2 (L/s·m^2) at a standard pressure, temperature, and air density.

[2]The resistance a material provides to the movement of moisture by diffusion is called *moisture permeance*. Permeance is a rate measured in perms, one perm being 1 grain of moisture/h·ft·°F.

sensitivity of fiberglass batt insulation to installation technique is, however, well documented—compression of the insulation reduces the delivered R-value and even small gaps or spaces left uninsulated can significantly reduce the thermal performance of the fiberglass batt (Brown et al. 1993; Trethowen 1991). Installations of this product have been observed and documented for the open-cavity spray application in the past and were observed as part of the applications trial in this case study. The expanding nature of the material and its installation produce consistent and complete cavity fill. Its performance is less installation-sensitive because cavity fill is a function of a chemical/physical expansion process rather than a function of the diligence of the installer.

Fiberglass insulation is a stable material and degradation over time is negligible. Friction-fit fiberglass batts are, however, susceptible to settling, dislocation, or water/wind damage under the conditions found in the transport of modular housing units. This is one reason that the modular industry was selected for further investigation.

Air Infiltration Barriers

The movement of air into and through the building envelope is a major cause of heat loss and moisture problems. The building codes, actions of building inspectors, and materials and techniques used by builders often do not reflect its importance. Building code officials, building inspectors, and many builders focus their efforts on the R-values of materials to increase the energy efficiency of homes and focus their efforts on vapor retarders and the control of diffusive vapor movement to prevent moisture accumulation in ceilings and walls. In both cases, the effects of airtightness are treated as secondary contributions to maintenance of the thermal and structural integrity of the building envelope. Research has shown that, in fact, air leakage into and out of the building envelope is a primary factor in controlling heat loss and moisture accumulation. Because air infiltration can account for between 25% and 45% of the total heat loss in a typical home (Goldschmidt 1986), concentration on the R-value of an insulation material alone yields far less than the total picture.

None of the major building codes, including the *Model Energy Code*, quantifies acceptable levels of air infiltration in residential structures. The *Model Energy Code* does make reference to the control of air leakage by caulking and sealing the building envelope "in an approved manner" (MEC-93, section 602.3.2), but this passing reference in no way establishes required techniques or materials to restrict air infiltration/exfiltration, nor does the code require or suggest a test to determine the airtightness of a residential structure.

Standardized test data indicate that the airtightness of the modified urethane foam insulation is comparable to the airtightness of conventional air infiltration barriers, more commonly referred to as "housewraps."[3] Because the codes do not make specific requirements for the airtightness of a house, clearly the elimination of a separate air barrier when this insulation is employed is acceptable building practice.[4]

Vapor Retarders

All four of the major model codes refer to either the *Model Energy Code* or an ASTM standard on vapor retarders. Both require a vapor retarder with at least a 1.0-perm rating on the warm-in-winter side of the building envelope (except in hot and humid climates). It is customary for the major codes not to specify material or techniques to achieve various requirements and this holds true for the 1.0-perm rating—no particular materials or techniques are specified.

Many builders and building inspectors do not fully understand the nature of moisture movement into and through the building envelope. Moisture can move into the building envelope in two ways—as the result of a diffusion gradient from areas of high moisture concentration to areas of lower moisture concentration or along with air as it infiltrates or exfiltrates the building envelope. Moisture movement associated with convection can dwarf the moisture movement by diffusion:

> It has been calculated that the movement of water vapor through a 2 cm (¾ in.) square hole as a result of a 10 pascal air pressure differential is 100 times greater than the movement of water vapor as a result of vapor diffusion through a 1 square meter (10 sq. ft) sheet of interior gypsum board (Lstiburek 1988).

Clearly, stopping the moisture carried by air leakage is more important than stopping the moisture carried by diffusion gradients.

Yet the most commonly used 1.0-perm vapor retarders, polyethylene sheeting, and kraft paper facing on fiberglass batts only address diffusive moisture movement without careful and complete air-sealing details. Application of vapor retarders without attention to the airtightness of the building envelope is equivalent to turning off a water spigot instead of fixing a broken water main. Even small points of air leakage can carry enough moisture-laden air to dwarf the amount of moisture movement retarded by a 1.0-perm vapor retarder.

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[3]Housewraps are typically spun-bonded polyolefin sheet goods. They are stapled to the exterior of the building shell after the shell is sheathed and before it is sided.

[4]One qualification made by the insulation manufacturer is the necessity of caulking areas of air infiltration that cavity foaming does not address—primarily the contact line between the bottom plate of exterior walls and the floor deck or other areas where framing-to-framing contact could lead to a point source of air infiltration. These limited areas are readily accessible during more than one stage of the construction process and can be easily caulked from the inside of the structure.

This is not to say that, in certain climates, 1.0-perm vapor retarders are not an important part of building envelope integrity. The focus, however, should first and primarily be on addressing the airtightness of a building envelope.

Standardized test data indicate that the perm rating of the modified urethane foam alone does not achieve the widely accepted 1.0-perm rating for moisture permeance in building envelopes. The moisture permeance of 3 in. or even 5 in. of the modified urethane foam (16 and 10 perms, respectively) is insufficient to meet the vapor retarder requirement. The insulation's control of convective moisture movement, however, permits the use of a vapor-retardant primer paint on the interior gypsum board to control diffusive vapor movement. The use of a 1.0-perm-rated paint primer is a more cost-effective form of vapor retardance than 6-mil polyethylene sheeting, as it does not require a separate task. At the local level, however, convincing building inspectors that 6-mil poly can be replaced by a vapor-retardant primer paint if the modified urethane foam is the insulation material may be difficult. Anecdotal evidence suggests that local building inspectors are less likely to accept the vapor-retardant primer because verification of its use is more difficult and inspection of the vapor retarder cannot be accomplished at the same time as inspection of the insulation.

Computer modeling of moisture movement in walls using a program (MOIST) developed by Burch suggested that a 1.0-perm rating was not required when the modified urethane foam insulation was used, except in climates as cold as or colder than Madison, Wisconsin (7,500 degree-days).[5,6] Further modeling would clearly provide a better understanding of the specific conditions for which a separate 1.0-perm vapor retarder is indicated with the use of different insulating materials and other building envelope components. Additionally, other conditions, such as indoor and outdoor relative humidity and active and passive ventilation, can have a substantial impact on moisture movement and must be considered in the design of the building and its envelope.

Functionally Equivalent Cost Comparison of Modified Urethane Foam and Fiberglass Insulation

Table 2 presents the installed costs associated with this modified urethane foam, fiberglass, other spray foams, and related building envelope materials.[7] At face value, the installed cost of the modified urethane foam is twice that of fiberglass. However, if the installed cost of additional materials required for fiberglass to be functionally equivalent to the modified urethane foam are added in—professional air-sealing, polyethylene wrap, and housewrap—then the modified urethane foam becomes quite competitive with the installed cost of a functionally equivalent system of fiberglass insulation. The functionally equivalent fiberglass system ranges in cost from $1.05 to $1.30 per square foot, whereas the installed cost per square foot of the modified urethane foam ranges from $1.00 to $1.09, depending on the need in very cold climates for some type of 1.0-perm vapor retarder. The fact that the modified urethane foam performs as a system of insulation, air sealant, and, to some degree, vapor retarder is a critical element of the overall comparison between the modified urethane foam and fiberglass batt insulation. Additionally, the installed cost of a new market entrant such as modified urethane foam may decrease relative to an established market player such as fiberglass if the modified urethane foam's market share increases and economies of scale and distribution come into play.

Table 2 **Installed Cost Comparison of Insulations**

Material	Installed Cost (ft^2) Equivalent Thickness
Fiberglass (unfaced)[a]	$ .50
Spray Urethane Foams	$1.25
Modified Urethane Foam System	$1.00 - $1.09
Functionally Equivalent Fiberglass System	$1.05 - $1.30
Polyethylene Wrap[b]	$ .09
Housewrap	$ .16
Professional Air-Sealing	$ .30 - $ .50
Standard Paint Primer (perm rating > 1.0)	$ .03
Vapor Retardant Primer (perm rating – 1.0)	$ .04

Sources: 1993 *Means Residential Cost Data; Journal of Light Construction*, Vol. 10, No. 9; "Assessment of Foam-In-Place Urethane Foam Insulations Used In Buildings," ORNL/Sub/86-56525/1.

[a]The installed cost of kraft-faced batt insulation was not available. Presumably the tar-impregnated paper and staples required for installation and the added labor of stapling the faced installation would increase the installed cost of faced compared to unfaced batts.

[b]Not generally included in the cost of installing a polyethylene vapor retarder are measures performed during the framing process that ensure a continuous barrier. These details include wrapping first- and second-floor rim joists and placing a poly strip above all top-floor interior walls. While these measures are not standard practice in the U.S., they are routinely done by Canadian framing crews and by more energy-conscious builders in cold-climate regions of the U.S. The costs of these vapor-retarding details are hidden in framing costs and are not a part of the costs as presented in this table.

A functionally equivalent cost comparison of fiberglass batts and the modified urethane foam insulation demonstrated the cost-competitiveness of the modified urethane foam insulation. Markets that value the functional advantages of the modified urethane foam with

[5]The MOIST computer modeling performed in this case study was done with limited variation of building envelope components other than the insulation; the effects of various types of exterior sheathing, siding, etc., would be likely to have a significant impact on moisture movement and accumulation.

[6]This conclusion was in general agreement with other computer modeling of moisture movement in building envelopes performed in Canada.

[7]The installed cost of the modified urethane foam is for the open-cavity, spray-applied application. Independently determined, installed cost figures for the closed-cavity application were not available.

respect to standard fiberglass insulation can be explored with the perspective this review has provided. The information available supports the position that the insulation should be considered as a material that can contribute to the overall increased energy efficiency of homes in the United States.

APPLICATIONS TRIAL

The objective of the applications trial of the modified urethane foam was to demonstrate the feasibility of cost-effectively incorporating the modified urethane foam installation process into the modular construction sequence. An arrangement was made to conduct the applications trial at the site of a modular home manufacturer. Originally, two identical modular homes were to be insulated, one entirely with fiberglass batts and the other entirely with the modified urethane foam insulation. To demonstrate the feasibility of incorporating the modified urethane foam installation process into the modular construction sequence, the insulation installation process for both insulations was to be observed and documented. Unforeseen circumstances led to the applications trial involving only the following:

- documented observation of both open-cavity spray and closed-cavity liquid modified urethane foam installation at the modular manufacturing facility and
- documented observation of closed-cavity liquid modified urethane foam experimental installation at the national laboratory.

Modified Urethane Foam Installation in the Modular Home

Background The model modular home to be insulated with modified urethane foam was a 2,800-ft^2 (37 ft by 40 ft), two-story salt box. The home was composed of six modules—three first-floor and three second-floor units. The layout of the modular units was such that the marriage walls ran parallel to the eave walls. Construction details relevant to the discussion of the modified urethane foam installation and the thermal performance of the modular home included the following:

- 2-by-6 wall framing, both 16–in. and 24-in. O.C.;
- 2-by -10 floor joists;
- OSB exterior sheathing throughout;
- ½–in. drywall glue-adhered and screw-fastened; and
- cathedral family room.

Application of the spray foam began when framing, drywall work, and wiring on the first module were complete. An experienced installer and assistant from the insulation manufacturer were present to perform the installation, and an analyst from the research center and the insulation manufacturer's vice-president/chief chemist were present to observe and document the installation.

The modified urethane foam fills cavity space when the two components are mixed and chemically react to produce the low-density, fine-celled soft insulation. The reaction is a rapid one and the components must be mixed in exact proportions right where installation is intended. This is accomplished by delivering the two components in separate hydraulic lines to a spray gun head. The process and the equipment are similar to that of the foam adhesive used by many modular manufacturers to secure ceiling drywall to the bottom chords of trusses or ceiling overlays. The component delivery lines are wrapped in insulation and an electric resistance heat coil to keep the components at the desired reaction temperature. The resulting 2- to 3-inch-diameter hose is quite heavy and can be cumbersome. The two components are stored in 55-gallon drums located next to the pump mechanism. The chemical reaction of the two components is temperature dependent, and the raw materials must be kept in a semicontrolled environment. The exact temperature of the components is achieved by agitation and heating at the pump. The resting temperature of the raw materials affects the start-up time of the application process. In this trial situation, the materials and pump were located on a truck just outside the plant. If located inside the plant, start-up times are approximately 15 to 20 minutes for both the spray and liquid, and changeover from one process to the other is reduced to approximately 20 minutes.[8]

Open-Cavity Spray Foam Application The modified urethane foam open-cavity spray application appeared to fit into the modular assembly process used by the modular manufacturer, with little accommodation required on the part of the modular crew and little change in the modified urethane foam installer's routine. Minor obstacles were encountered that were overcome or could be overcome with little impact on the modular assembly process. Spray application can be accomplished with one experienced applicator and occasional unskilled assistance from another worker. Suspension of the modified urethane foam hose from a gantry could result in significant efficiency gains and elimination of the occasional assistance the installer required.

The modified urethane foam installers must go through a certification process and a training period. It is likely that any modular manufacturer using this product as its insulation and air-sealing system would train a modular crew member as the insulation installer. An employee familiar with the modular construction process would speed efficient incorporation of this insulation and air-sealing system into the modular construction

[8] If separate setups are employed for each formulation, changeover times are eliminated.

process. It is also possible that use of this insulation material could result in labor or material savings by eliminating current air-sealing practices.

Closed-Cavity, Liquid-Injection Application The liquid application of the modified urethane foam in closed cavities involves the same proportion of base components but requires much greater force to pump the liquids through the injection lines. A test pour was performed in which the liquid modified urethane foam was shot into an empty cardboard box approximately one cubic foot in volume. The liquid material expanded to its final volume in approximately five minutes. The filled cardboard box was then sawed in half to inspect the materials consistency throughout the test sample. The expanded foam was light yellow in color, had the consistency of a foam seat cushion, and was uniform in appearance. The modified urethane foam installers indicated that the test shot was satisfactory.

Preparation was required for closed-cavity liquid injection. Framing details (location of studs, window cripples) were most easily marked along the very bottom of the rim joist before exterior sheathing was secured. Marking framing locations before sheathing was particularly important around window and door frames because the 16- or 24-in. O.C. framing members adjacent to jack studs often resulted in very narrow framing pockets. Care was also taken to mark those cavities that could not be injected. Stud cavities two feet in on the marriage wall were not sheathed (i.e., were not closed cavities) and therefore could not be liquid injected. These open cavities were, however, later insulated with spray-applied modified urethane foam. The framing cavity for the chimney chase was not drywalled and was marked for exclusion.

Two-inch holes were drilled in the exterior sheathing as liquid injection and venting points in each cavity. The holes were approximately four feet above the bottom plate and just below the bottom of the lower top plate. The upper row of injection holes were drilled from staging or a step ladder. On the eave walls, both drilling and insulation injection could be done on two units at a time because the eave walls of adjacent units were located close enough on the assembly line for this to be accomplished. Approximately four holes were drilled per minute (this is straight drilling time and does not include movement of the worker from one wall to the next or the movement of staging for the top row of injection holes).

As with spray application, two installers were present as well as a supervisor. In actuality, only one worker need be a certified installer—auxiliary tasks such as hose hauling, overfill trimming, cavity marking, and hole drilling could be performed by any crew member. A respirator was not necessary for any of the liquid injection work.

One gable end wall, which was framed 2-by-6, 16-in. O.C., was liquid injected in approximately 21 minutes. The wall space to be insulated was 14 ft by 8 ft (11 bays), with two bays at the marriage wall not drywalled and, therefore, not injected.

Minor obstacles were encountered during the injection process, with solutions either created at the time or suggested for future application. The single major obstacle encountered during the modular manufacturer's installation was drywall failure associated with closed-cavity liquid injection. On nine separate occasions, injection of liquid modified urethane foam resulted in drywall bulging significant enough to require removal and replacement. Efforts by the modified urethane foam installers to adjust the injection process, either by decreasing the duration of each injection (from 10 seconds to 3 seconds) or by increasing the time between injections, seemed to have little effect. Cavities were eventually successfully injected but only after the end of the regular workday, when the installers could proceed entirely at their own pace.

Although the force of expanding foam has in previous tests resulted in some bulging of drywall,[9] the number and extent of the failures at the modular manufacturer's presented a real problem and a puzzle for the modified urethane foam crew and observation team. It became essential to determine the conditions that led to the unsuccessful closed-cavity fill. The following is a list of conditions that occurred at the installation that may have contributed to the failures:

- *Initial moisture content of gypsum wallboard*—The moisture permeance of gypsum board for both the paper faces and the gypsum core is quite high—34 perms (USGC 1992). Gypsum board readily absorbs and releases airborne moisture. Several days of rain in the area at the time of the modified urethane foam installation had created high-humidity conditions both inside and outside the plant. The modular manufacturer attempts to keep gypsum board lifts stored inside the plant, but it is not uncommon for lifts to be stored under the extended eaves of the assembly plant, similar to the manner in which gypsum board is stored at retail building supply centers. Located here, the gypsum board lifts would be protected from direct contact with liquid moisture but are susceptible to atmospheric conditions or even windblown rain or mist. Inspection of the gypsum core in an area of cavity fill failure revealed the core to be paste-like in texture instead of the chalky, crystalline texture normally encountered in the gypsum core.

[9]The Florida Solar Energy Center (FSEC) observed drywall bulging both in tests performed for their observation and in the Canadian energy-efficiency demonstration home, the "NEAT House" (from a trip report by Armin Rudd, research analyst for the FSEC).

- *Gypsum board moisture gain from other sources*—The chemical reaction of the expanding modified urethane foam generates water vapor and elevated temperatures. Additionally, some areas of the modules were being spray-painted just prior to or during closed-cavity, liquid injection of the modified urethane foam. Both are possible additional sources of gypsum board moisture gain.
- *24-inch O.C., 2-by-6 framing*—Both the spanning distance between framing members and the total volume of the cavity served to increase the stress placed on the gypsum board during liquid injection. The installers indicated that 24-in. O.C. or 2-by-6 framing had not caused problems in the past, but the combination of the two had not been encountered prior to this installation. All but one incidence of drywall deformation occurred on a 24-in. O.C. framed wall, suggesting that the dimensions of the framing cavity may be a determinant of deformation.
- *Duration of injection shots*—The installers decided to go with larger and fewer injection points and longer continuous injection shots than standard practice at the installation in an effort to meet the modular construction schedule and, per the request of the modular home manufacturer, reduce the number of holes in the exterior sheathing.
- *Changeovers from the two formulations*—Because the same delivery lines were used for both spray and liquid modified urethane foam applications, there was the possibility of spray formulation remaining in the delivery lines, thus contaminating the liquid application. One of the primary differences in the two formulations is the amount of catalyst that controls the rate of chemical reaction and hence the expanding force of the material.

No attempt to prioritize or rank the effects of each of the above was made until a second observation of closed-cavity liquid injection provided additional information. A summary of the modular manufacturer's closed-cavity, liquid-injection application follows the national laboratory's trial application.

CLOSED-CAVITY, LIQUID INJECTION AT A RESEARCH CENTER

Background

Under a separate DOE contract, the modified urethane foam closed-cavity, liquid-injection process was being evaluated for its feasibility in retrofit application. In the first phase of this project, the ability to use the closed-cavity, liquid-injection process in a laboratory test was to be demonstrated. The research center was invited by laboratory staff and the modified urethane foam manufacturer to observe the retrofit application test. This observation served as a second opportunity for the research center to assess the closed-cavity, liquid-injection process.

Installation

Prefabricated wall sections were to be insulated with modified urethane foam. Four wall panels were constructed for the laboratory experiment by a local educational facility. The panels were constructed as follows:

- *framing*: yellow pine 2-by-4s;
- *exterior sheathing*: ½-in., nonstructural, asphalt-impregnated fiberboard;
- *siding*: 3/8-in. hardboard clapboard (8-in. exposure);
- *interior sheathing*: ½-in. paper-faced gypsum board (painted with a white latex paint); and
- *fasteners*: 1¼-in. ring-shank drywall nails.

Preparation for closed-cavity injection of modified urethane foam insulation from the interior side of the wall panel included a test shot of the liquid formulation and estimation of the initial relative moisture content of the gypsum board core. A moisture meter was inserted approximately ¼-inch deep into the drywall of the wall panels at various locations to determine the relative free moisture content of the gypsum board core. The meter used is typically used for estimating the free relative moisture content of wood, but works with gypsum board as well. Table 3 gives approximate conversions for wood and gypsum board.

The initial free moisture content of the gypsum board was estimated at .25%. This estimation was based on more than six observations, all of which were in close agreement. Technical staff from a major gypsum board manufacturer indicated that, given the controlled, conditioned environment of the test facility, this was a reasonable gypsum board free moisture content.[10]

Closed-Cavity, Liquid-Injection Application

The injections of the first two wall panels were photographed and thermally imaged and the thermography video-recorded. Alternate cavities were injected with a shot whose duration was determined by installers approximating the volume of space to be filled. The modified urethane foam installers were two of the company's most experienced. One of the installers at the lab test was also present at the installation at the modular home manufacturer's site. The following points are important as they relate to the conditions encountered at the modular home closed-cavity, liquid injection.

- *The installers were not under any time constraints at the lab test installation.* More laboratory-like conditions

[10]Jack Hodges of Domtar Gypsum provided technical information on the relationship between moisture content and the strength of gypsum board.

Table 3 Moisture Content Conversion Table[a]

Wood (% Relative Free Moisture)	Gypsum Board (% Relative Free Moisture)
10	.25
15	.60
20	1.00
25	1.50
30	4.00
35	5.00
40	6.5
50	7.00
60	8.00
70	8.5

[a]This conversion table (revised 6/91) was obtained from Tom Laurenzi of the Delmhorst Instrument Co., Towaco, N.J.

were encountered at the lab than the production line conditions at the modular manufacturer.

- *Moisture meter readings shortly after injection were found to rise from .25% to an average of .6% in areas near or above the injection fill line of the expanding foam.* This coincided with thermal images indicating a significant rise in temperature in the injected cavities. The unfilled spaces above partially injected cavities were significantly higher in temperature, presumably due to rising warm water vapor being given off as the expanding foam set.
- *The rapid rise in free moisture content associated with heat and moisture generated by the expanding foam was followed by an equally rapid drop back to the initial free moisture content.* Within one-half to one hour, the moisture readings in the gypsum board core returned to the .25% range.
- *Measurements made on the planar surface of the gypsum board to check the wall straightness before and after closed-cavity, liquid injection indicated no drywall deformation.* The pressure exerted by the expanding foam did not result in any failure or deformation of the framing/gypsum board interface.
- *Cavity injection of modified urethane foam under conditions simulating the surface wetting associated with spray painting resulted in no bowing or drywall failure.* Two full-length, 16-in. O.C. wall cavities on the third wall panel were dedicated to experimentation with surface wetting of the finished drywall surface. In the first test, approximately 16 fluid ounces of water were sprayed over a period of one-half hour onto the gypsum board surface. The estimated free moisture content of the gypsum board core obtained just 15 minutes after spraying was approximately 1% and as high as 1.5% after one-half hour. No wallboard deformation was observed in this test.
- *In a second wetting test, virtual soaking of the painted drywall surface resulted in no bowing or drywall deformation after injection.* Efforts were made to increase the moisture content high enough to force the injection to breach the cavity. No drywall deformation was observed.
- *Soaking the drywall surface and doubling the duration of the injection shot resulted in no drywall deformation.* In a final test of the effects of wetting and driving up the free moisture content of the gypsum core and paper surface, the drywall was "soaked" and the shot duration of liquid injection was more than doubled in an attempt to force bowing or drywall failure. The shot duration was as great as the duration used initially at the modular manufacturer. No failure or deformation of the drywall occurred as a result of these conditions.

Comparison of Lab and Modular Manufacturer Closed-Cavity Applications

The different conditions encountered in the laboratory and modular manufacturer trials dramatically affected the outcome of the closed-cavity, liquid injection of the modified urethane foam. Efforts at the lab to create moisture conditions and/or increase the rate of injection that would induce drywall deformation were unsuccessful. These results imply that conditions at the modular manufacturer's other than or in addition to the gypsum board moisture gain from the injection process/coincidental spray-painting or the rate of injection were responsible for drywall deformation. The following is a list of remaining differences between the two trials at the lab and at the modular manufacturer's:

Condition	Modular Manufacturer	Lab
Exterior sheathing	½-in. OSB	½-in. fiberboard
Drywall adhesive	Yes	No
Formulation changeover	Yes	No
Initial free moisture content	unknown	.25%
Number, size, and distribution of injection holes	2 two-inch, one mid-wall, one at top	7 one-inch, three across top of cavity
Cavity dimensions	2-x-6, 24 in. O.C.	2-x-4, 16 in. O.C.

Exterior Sheathing The sheathing materials used at the lab and at the modular manufacturer's were different in two principal ways: rigidity and surface finish. OSB is much stiffer than fiberboard and has a denser, smoother surface. The fact that no deformation in the fiberboard was observed at the lab indicated that the greater rigidity of OSB was not a factor in the different results.[11] The comparable impermeability to moisture of both the surface of OSB and tar-impregnated fiberboard indicated that this difference was not a factor either.

[11]At the lab, the fiberboard was trapped to the framing by the clapboard siding. At the manufacturer's, the modified urethane foam installation occurred before the vinyl siding was applied. No impact to the results of the two trials could be identified based on the presence or absence or type of siding applied.

Drywall Adhesive The drywall adhesive used at the modular manufacturer's site created a continuous contact bonding the backside of the gypsum board to the wall framing. A chemical reaction between the drywall adhesive and the modified urethane foam could conceivably contribute to a weakening of the wallboard. Although the research chemist felt that chemical interaction between the adhesive and the setting foam was very unlikely, tests were performed to observe their interaction. The tests indicated that there was no chemical reaction between the adhesive and the expanding foam.

Formulation Changeover Prior to the closed-cavity, liquid-injection at the modular manufacturer's site, open-cavity spraying was performed, requiring a changeover. Only closed-cavity, liquid-injection was performed at the lab. Line contamination of spray formulation at the modular manufacturer's could have had a significant impact on the expansive force of the foam.

Initial Free Moisture Content The initial free moisture content of the gypsum board was not measured. The high humidity and heavy rain just prior to and during the modified urethane foam installation, the possible storage of the gypsum board in a semi-sheltered location, and the paste-like consistency of the gypsum core after wall failure all suggested, however, that the initial free moisture content of the drywall at the modular manufacturer's was significantly greater than the initial free moisture content of the drywall at the lab.

An experiment was conducted to estimate just how high the gypsum board initial free moisture content might have been at the modular manufacturer's site given the environmental conditions just prior to and during the modified urethane foam trial application. Fourteen-inch squares of ½-in. gypsum board were placed in positions in which their exposure to moisture was similar to storage conditions at the modular manufacturer's: protected from above and to one side from rain but open on at least two sides to outside air, fog, and windblown rain. The moisture readings of the gypsum core in this experiment varied widely, but free moisture contents of 1% to 4% were not uncommon during damp and rainy conditions. Because the squares were singly placed and drywall is typically stored in lifts of 30 to 90 sheets, free moisture content may vary throughout a stack. It is at least possible, given the results of this experiment, that the gypsum board free moisture content prior to modified urethane foam injection was as high as 1% to 4%. This is 4 to 16 times greater than the initial free moisture content of the gypsum board at the lab.

Number, Size, and Distribution of Injection Holes It is standard installer practice for a smaller diameter and greater number of injection holes per cavity to be made in a retrofit installation than in new construction. Greater uncertainty regarding method of construction, drywall attachment, and cavity obstructions in retrofit installation requires a more deliberate approach. The test at the lab, in which the duration of liquid modified urethane foam injection was more than doubled and at least one intermediate injection hole was bypassed without any drywall deformation, suggests that the number and diameter of injection points was not a primary cause of the failures at the modular manufacturer's. The three holes across the top of each framing cavity at the lab were so located in response to the number of voids in the upper corners at the modular manufacturer's. No mechanism for their impact on cavity deformation was identified.

Cavity Dimensions The different framing cavity dimensions at the modular manufacturer's (2-by-6, 24-in. O.C.) and the lab (2-by-4, 16-in. O.C.) had two important effects: increasing the lateral span from points of drywall framing attachment and increasing the depth of the framing cavities. An increase from 14½ inches to 22½ inches represents a 55% increase in the spanning distance. Because the relationship between the resistance of any material to deflection and spanning distance is cubic, this 55% increase in span results in at least a tripling of the force required to resist the same deflective force. Clearly, the 24-in. O.C. framing schedule results in a large decrease in the spanning material's ability to resist deflection.[12] Additionally, a 2-by-6 framing cavity has 63% more depth than a 2-by-4 framing cavity. For a given width of a framing cavity, this increase in depth represents the potential for increasing the lateral force exerted by expanding the foam.

COMMENTS

The number of variables between the modular manufacturer's and the lab's tests prohibits specific identification and quantification of the determinants of drywall deformation. The evidence from the lab's modified urethane foam installation suggests that the deformations experienced at the modular manufacturer's plant were related primarily to a combination of the following factors:

High initial free moisture content of the gypsum board—While the free moisture content of the gypsum board prior to foam application or any spray-painting at the modular manufacturer's was not measured, it is probable that the atmospheric conditions and drywall storage location led to initial free moisture contents significantly higher than the moisture contents recorded at the lab. Tests at the lab with surface wetting suggested that this increase in initial moisture content alone was insufficient to lead to drywall deformation. Higher initial moisture content in conjunction with moisture gains

[12] According to the *Gypsum Construction Handbook*, standard, ½-in. gypsum board can be used with either a 16- or a 24-in. O.C. framing schedule.

from the modified urethane foam chemical process and spray painting, however, may have resulted in free moisture contents significantly greater than any moisture contents recorded at the lab.

Technical staff at a gypsum board manufacturing company indicated that ½-in. gypsum board's modulus of elasticity can drop from 500,000 at .25% free moisture to less than 200,000 at free moisture content just above 1%.[13] Because the modulus of elasticity is a measure of a material's resistance to deflection, significant reduction in this measurement indicates a lower ability of the material to resist the expanding force of the modified urethane foam.

Framing cavity size—Increasing both the spanning distance and the depth of the cavity resulted in significantly reduced ability of the drywall to resist the expanding force of the modified urethane foam. While the modified urethane foam installers had prior closed-cavity experience with 2-by-6 framing and 24-in. O.C. framing schedules, the application at the modular manufacturer's site represented the first installation where both were employed.

The contribution to deformation of line contamination due to formulation changeover at the modular manufacturer's could not be determined. Staff from the insulation manufacturer felt that the possibility of contamination was significant enough to warrant a change in installation procedures that is discussed in the recommendations at the end of this report.

Summary of Closed-Cavity, Liquid-Injection Application

The closed-cavity, liquid-injection process requires careful planning, preparation, and application. The inability of the installers to observe and inspect the installation requires careful consideration of factors that will have an impact on the manner in which the liquid injection fills the framing cavity as the liquid material expands to foam. As environmental conditions or building techniques and specifications vary, the impact these variables have on the injection process must be anticipated because the consequences of improper installation can be difficult and/or expensive to rectify. Any review of the installation at the modular manufacturer's must be prefaced with the fact that the original schedule of events called for modified urethane foam installers to liquid-inject 17 modular units before insulating the model home.

- *Careful planning*—Because switching from one modified urethane foam formulation to another is time consuming and involves purging of delivery lines, the insulation of walls, ceilings, and floors must be carefully sequenced with respect to the existing modular assembly schedule. Alternatively, in a large operation, two separate equipment setups may be required. The fact that one home and its exterior envelope exist in the plant as individual modules requires foresight on how the modules will ultimately link to create an airtight building shell. As the modified urethane foam air-sealing and insulating system is incorporated into any modular assembly process, line foremen or plant management must be responsible for keeping the "big picture" in clear view to ensure that all parts of the exterior envelope have thermal integrity. Initially, the installer may need to boldly label or mark framing cavities that require insulation with a different formulation, insulation at a later stage in the assembly process, or resolution by superiors.
- *Careful preparation*—The nature of the injection process requires the complete attention of the modified urethane foam installer. All wall preparation should be done well before liquid injection. Hole-drilling and careful marking of framing cavities, especially cavities requiring an injection load that is larger or smaller than usual, should be done before installation to allow the installer to focus on the injection process.
- *Careful application*—At this stage of its development, the closed-cavity, liquid-injection process appears to be a combination of science and art. The installers at both the modular manufacturer and the lab demonstrated a certain experience for the correct combination of temperature, pressure, fill rate, and timing of consecutive cavity fill. As experience is gained with the closed-cavity process in varying construction situations, an installation manual and installer's training course will help to reduce the element of art involved in the installation process and increase the element of science. Because the moisture content of gypsum board appears to be an important element of successful cavity fill, use of a moisture meter prior to closed-cavity injection may ensure the installer of conditions suitable for the process.

Much has been gained from the two documented observations, allowing technical staff to benefit from a broader range of information and expertise on the development of the closed-cavity, liquid-injection process. No other non-CFC/HCFC, air-sealing foam insulation exists with the potential for broad-based closed-cavity fill. At a minimum, the modified urethane foam closed-cavity process has demonstrated significant potential for modular application.

CONCLUSIONS

Based on the best available evidence from the literature, advice from experts in the field of building envelope

[13]Based on telephone conversations with Jack Hodges, technical representative for Domtar Gypsum headquarters in Michigan.

assembly, and computer modeling of moisture movement, insulating with this modified urethane foam eliminates the need for most separate air-sealing details and a separate vapor retarder in most climates.[14] Elimination of air-sealing details, a separate air infiltration barrier, and a separate vapor retarder makes the installed cost of this modified urethane foam and a functionally equivalent fiberglass insulation system comparable. This means that builders seeking to significantly increase the energy efficiency of the homes they build can do so with this product in a cost-competitive manner. The ability of the expanding foam insulation to adhere to framing and fill all cavities makes it less sensitive to framing irregularities and capable of achieving high-quality and consistent thermal integrity without painstaking attention to insulating and air-sealing details. Additionally, other spray-applied foam insulations with higher R-values cannot compete cost-effectively with this material and do not have the potential to insulate closed cavities.

The open-cavity, spray-applied modified urethane foam process demonstrated quality and consistent cavity fill. The process appeared suitable for incorporation into the modular assembly process, with little change required in modular operating procedures or construction sequences. While installer training appeared to be important to the proper application of the insulation, the skill level required for spray application was not substantial.

The closed-cavity, liquid-injected modified urethane foam process demonstrated less consistent cavity fill, and conditions encountered at the modular manufacturer's led to installation problems that would prohibit, if not corrected, incorporation into the modular assembly process. A second observation of the liquid injection process at the lab led to a better understanding of the conditions resulting in the drywall deformations at the modular manufacturer's and improved methods for achieving successful application. The second observation revealed no drywall deformations or insulation voids. Drywall deformation at the modular manufacturer's was likely to be related to high initial moisture content of the drywall, reduced resistance to drywall deformation associated with 24-in. O.C. framing cavities, and accelerated reaction time associated with possible contamination of liquid formulation with spray formulation. Voids in the closed-cavity installations at the modular manufacturer's were likely to be related to a pattern of injection holes that caused a constriction inside the cavity, impeding the rise of the foam.

The closed-cavity, liquid injection process is important to consideration of the modified urethane foam as a whole-house insulating and air-sealing system. It eliminates the disposal and labor costs associated with trimming spray-applied overfill, has the potential in site-built homes to release the installation of insulation from a specific stage of construction, and opens new markets such as modular and retrofit. The observations at the modular manufacturer's and the lab of the liquid injection process reinforced this potential. The installation problems at the modular manufacturer's site indicate that final development of the liquid injection process requires fine-tuning of the installation process and more exacting delineation of the interaction between building materials and the expansion process.

[14] Air-sealing details between floor decks and bottom plates and between rough openings and windows and doors are still required. Additionally, in very cold climates (greater than approximately 7,500 degree-days), elimination of a separate vapor retarder is indicated with this insulation foam if used in conjunction with a vapor-retardant primer paint.

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