Energy-Efficient, Flood-Damage-Resistive Residential Envelope System Testing

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ABSTRACT

This paper presents the history, current status, and plans for a project to test the flood damage resistance of various energy-efficient residential building systems under field conditions. The Oak Ridge National Laboratory and Tuskegee University are developing this three-task project as part of the Partnership for Advancing Technology in Housing (PATH). Task I has accomplished the planning and design of the experimental facilities, test modules, and protocol development for the project, which is reported in this paper. Task II began in early 2001and is testing both traditional residential envelopes and those with potential flood damage resistance under representative flooding (wetting) and drying conditions. The response of envelope systems to flood-induced structural damage and to the impact of various waterborne contaminants is not currently addressed by this project. Task III will develop computer models to predict the performance of materials and systems under various flooding and drying conditions.

INTRODUCTION

The Federal Emergency Management Agency (FEMA) estimates that about 4 million residences and 2 million non-residential structures existing within the United States are vulnerable to flood damage (lowest occupied floor below flood level). Houses that are not "substantially damaged or modified" (repairs or alterations exceeding 50% of the pre-event market value of the building) can be rebuilt to pre-flood conditions with new technologies that would reduce the level of potential future flood damage. Some of these new technologies (e.g., foam plastic insulation) also have enhanced energy efficiency properties. These technologies can also be applied to an even broader group of homes with "finished" basements that can be subjected to water damage from broken water pipes, sewer backups, or "failed" sump pumps.

Existing and developing technologies can be employed to profoundly reduce the impact and outcome of future floods. To be effective, they must be applied either during initial construction, incorporated during modification or additions to an existing home, or incorporated during the rehabilitation of flood-damaged homes.

FEMA's mitigation web site notes various mitigation concepts and recommended strategies. Some of these concepts and strategies can also improve the energy efficiency of the home. To date, little or no effort has been expended to demonstrate and validate the potential additional benefits of energy-efficient technologies to reduce the damage and reconstruction costs following floods. Water-damage-resistive residential construction is currently economically feasible in flood-prone and storm surge areas. The potential also exists for the development of waterproof construction that would protect both the house and its contents.

The potential for developing energy-efficient, flood-damage-resistive residential envelope systems was observed by the principal author, Robert Wendt, in 1998. While working on other retrofit technology projects, Wendt identified several existing materials that appeared to have significant potential to resist flood damage. These included a cellulose-reinforced gypsum wallboard (without paper faces) and various closed-

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cell plastic foam insulations. He informally experimented with these materials by immersing them in water for three days and then allowing them to dry naturally. These materials showed little or no adverse impacts from having been immersed.

While the individual materials had positive properties, the question remained how would they perform when placed within residential building systems. In 1999, a proposal was put forward to the Departments of Energy (DOE), Housing and Urban Development (HUD), and the Federal Emergency Management Agency (FEMA) as part of the Partnership for Advancing Technology in Housing (PATH). This proposal outlined an approach that became the basis for the project that is the subject of this paper.

At about the same time, FEMA was completing work on an effort to bring the newly published International Code Series into compliance with the minimum requirements of the National Flood Insurance Program. Among the new International Code provisions is a requirement to use flood-damage-resistive materials in areas vulnerable to flooding. FEMA was interested in developing appropriate test methods to evaluate the performance of building materials used below the base flood elevation (BFE). In addition to supporting this project, FEMA also sponsored the development of a laboratory testing protocol for use with individual materials. This protocol was developed by the National Evaluation Service (NES) and is available on the NES web site at http://nateval.org.

An ORNL research initiative in the area of assessing the hygrothermal performance of building envelope systems and subsystems is a complementary activity that will be tapped for developing performance evaluations of water-resistant envelope structures/buildings.

This research initiative is aimed at providing directions for the design of building envelope systems (e.g., walls and foundations) in terms of their whole performance under conditions where flooding has occurred. Whole performance includes such issues as energy efficiency, moisture performance, indoor air quality after flooding, and system and subsystem durability performance. This integrated approach will use building science principles, coupled with material performance and adjusted by the reality of field data, to develop a set of envelope systems.

The performance properties of these systems and subsystems will be supplied to advanced hygrothermal and damage models, which will be complemented and benchmarked by laboratory and field results. These models will then be used to provide predictions of the response of the envelope system to a wide range of climatic conditions and hygrothermal stresses (such as during flooding).

For the first time, this project will quantitatively investigate the following:

- Understanding the fundamental processes of water uptake by various construction materials.
- The effect of duration of the flooding event on water storage (sorption) at both the material and system level (layered wall system).
- The dimensional changes and physical changes in material properties during and after a flood event.
- The biological mold growth possibility.
- The quantification of the drying period for a variety of wall systems and climatic conditions.

Currently, decisions on remedial work are largely based on past experience, and these decisions are usually skewed towards conservative actions.

PROJECT OBJECTIVES

The objective of this project is to scientifically investigate the impact of representative flood water on the performance of traditional residential envelope systems, as well as those systems with the potential to effectively resist damage from exposure to flood water. The testing will study the failure mechanisms associated with the wetting and drying cycles in traditional construction to determine what happens, how and when it happens, and why it occurs.

This project has chosen to address the impact of a riverine floodwater on the performance of residential envelope systems. The water source used will be a rural man-made lake within an agricultural area. While not representative of all potential floodwater conditions, the lake will provide water with suspended solids, microorganisms, and "contaminants" typical of rural locations.

The experimental testing will be accomplished at a full-scale, complete system level. This will permit an enhanced understanding of not only how individual materials perform but also how they will perform when combined into a multi-element system. Among other things, testing building systems will identify those individual materials that pass flood damage resistance testing alone but fail when combined into a system.

Wetting will be accomplished in the field using controlled flooding (minimum water movement and no debris) with untreated lake water, which has many of the properties of water found in a riverine flood. Drying will be based on the ambient weather conditions at the experimental site because this represents real world conditions. Initially, the tests will have minimal intervention in the drying process with only the door and window of the test module being opened to facilitate air movement through the module. More active intervention (fans, heater, dehumidifier) may be considered in later tests.

The focus of the testing will be on wetting and drying as the cause of flood damage. It will also address material property changes and the restorability of the materials to their original appearance and intended purpose. In order to minimize the variables in the experiments, the testing in this project will not address other potential forms of flood damage such as those associated with moving water (tides and currents), waterborne debris, or unique waterborne contaminants (e.g., fuel oil, sewage, etc.). Including these other forms of flood damage would add the loss of structural integrity due to lateral forces, mechanical damage due to impacts and lateral forces, and chemical and biological decontamination to the already significant list of variables.

Based on the experimental findings, various tools will be developed to assist in the selection of flood-damage-resistive envelope systems by those involved in the construction or reconstruction of housing in flood-vulnerable areas of the nation.

PROJECT APPROACH

A three task project of (1) planning, design, and systems testing protocol development; (2) testing, performance evaluation, and information dissemination; and (3) analysis and modeling and information dissemination has being launched to verify and predict the performance of various materials and systems under actual flooding conditions. The project's approach will be to

- identify and document the impact of flooding on current residential envelope construction practices and
- identify, evaluate, and test methods of minimizing or eliminating the damage caused by exposure to water of potential residential envelope systems.

Baseline modules that resemble and represent various typical residential construction types will be used to identify the impact of floodwater on current construction practices. In addition, several water-damage-resistive test modules would be used to show the impact of enhanced construction practices. It is likely that this testing will result in an evolution of the recommended approach, since failures are possible at each stage.

There are a number of technical documents that discuss flooding, flood damage, flood protection, cleanup after the flood, as well as other documents covering flood zone regulations and the National Flood Insurance Program (NFIP). While all of these documents impact how houses are to be built or restored if they are subjected to flood hazards, the following is a listing of technical documents that directly relate to this project.

1. FEMA, *Engineering Principles and Practices for Retrofitting Flood Prone Residential Buildings*, January 1995.

   This document discusses the various methods of retrofitting houses, the regulatory framework, analysis of flood hazards, benefit/cost analysis and alternative selections, and general design principles. This document provides for the strategy of wet flood proofing of an existing house if it has not been substantially damaged or improved (> 50% of the pre-flood market value). It is this provision that justifies the evaluation of the performance of current and innovative building systems to resist flood damage.

2. FEMA Technical Bulletin 7-93, *Wet Flood Proofing Requirements*

   This document discusses the impacts of flood duration, flood-borne contaminants, flood frequencies, and depth. It also presents engineering considerations for the primary elements of a building. This project will evaluate how current and innovative building systems perform against these considerations.

3. FEMA Technical Bulletin 2-93, *Flood-Resistant Materials Requirements*

   This document classifies the flood resistance of individual materials in five categories, three of which are considered "unacceptable" and two of which are "acceptable." It lists the basis for classifying materials and then evaluates individual materials as to their ability to resist flood damage. It does not evaluate the performance of "systems" made from a combination of several of these materials. This project will evaluate both individual materials and systems performance when subjected to common riverine flood conditions.

PROJECT DESCRIPTION

In addition to the project staff at ORNL and Tuskegee, nine advisory panel members and four peer reviewers that represent an appropriate mix of interests related to flood-resistive materials and systems were identified and invited to take part in this effort. These included senior technical staff from various building material manufacturers, representatives from state and government agencies involved in such work, and architects and engineers from academia. The industries represented included dry wall, plastic foam insulation, wood products, residential siding, gypsum board, windows and doors, and homebuilders. The government agencies included were FEMA, ORNL, Southern Building Code International, and Forest Products Laboratory. A representative from the National Evaluation Service was also included as a peer reviewer. The role of the advisory team and the peer reviewers includes the following:

- Review the project's proposed approach, provide ideas and insights relative to the appropriateness of planned testing.
- Assist in the identification of systems to be tested that are cost-effective, functional, etc.
- Identify industry participants and/or contacts to bring into the process.

The advisory team met in August 2000 and reviewed the draft testing protocol and the testing plan for Task II.

Task I. Planning, Design, and Protocol Development

This task was completed at the end of 2000. It included testing protocol development, experimental facilities design, and test module design.

Testing Protocol. The first task in this effort is the development of a protocol for field testing of flood-damage-resistive residential envelope systems (Aglan and Wendt). The protocol serves as a guideline for experimental procedures, testing, and evaluation of performance of the envelope system. This test method consists of placing a test envelope module in a full-scale outdoor basin, immersing it in floodwater according to a specific testing program, observing, measuring, and recording the performance changes and any distress or failure of the envelope assembly during and after the test.

The scope of this protocol involves the following:

- Steps that should be followed in testing residential envelope systems to determine the extent of their flood damage resistance under static flood conditions (i.e., no lateral water movement).
- Procedures for determining the flood damage resistance of residential envelope systems through field testing under simulated flood and drying conditions.
- Simulation of conditions that are representative of those typically found in floods. Performance determination by this method relates to the ability of elements or materials of the building envelope to remain functional during and after a flood. This includes, but is not limited to, items such as interior and exterior walls, floors, windows, doors, insulating materials, siding, etc.
- A systematic approach to test flood-resistive residential envelope systems, including the identification of needed information, the performance of tests, the interpretation of data, and the reporting of results.

Experimental Facilities Design. Two basins are being constructed at the Tuskegee University research farm that will permit the simulation of riverine flood conditions. One basin will contain a slab-on-grade foundation for the test modules. The other basin will contain a stem wall foundation for testing flooring systems with a crawl space. The design of the basins will facilitate the construction or placement of a number of small test modules and flooding them to a level of 2 feet above their floor level. The rate of flooding and draining and the length of immersion will be controlled. The basins will be built to permit testing of different modules. The configuration and orientation of the basins simulate actual post-flood drying conditions by permitting sunlight and wind to reach the test modules (see Figures 1a and 1b).

Test Modules Design. Test modules measuring approximately 8-by-8-by-8-ft high are planned to represent the various residential construction systems (see Figures 2a and 2b). The first two modules to be built will reflect traditional residential building methods and materials. Module C1 will be built with a crawl space, on a stem wall and continuous concrete footing. Construction will be wood-frame with a number of differing claddings and interior finishes. Module S1 will be similar with the exception of being built on a concrete slab-on-grade. Subsequent testing will use similar modules but with the substitution of potentially flood-damage-resistive materials and systems. The specific module designs for these tests are still under development.

Task II. Testing, Performance Evaluation, and Information Dissemination

This work began in early 2001 and will extend through late 2002. It includes the construction of an experimental facility and test modules as well as immersion testing of six to ten modules. The first two tests of traditional residential construction will establish a baseline for testing and evaluation. The outdoor conditions will be monitored and recorded using a weather station. Differences in the drying conditions due to the weather will be incorporated in the modeling. Comparative assessment will be performed based on outdoor conditions. The later tests will evaluate the actual flood damage resistance of various potential materials and systems and may include development and evaluation testing for manufacturers. Finally, the findings of this work will be disseminated in the form of a Best Practices Guide.

Baseline Testing and Evaluation. A baseline of current construction practice will be used for evaluating the performance of potential flood-damage-resistant materials and systems. This baseline will be created with modules C1 (crawl space) and S1 (slab-on-grade) constructed in the basins and tested under the following conditions:

- The basins will be flooded to a level of 2 ft above the respective floor levels.
- The simulated flood (immersion) will continue for 72 hours.
- The filling and draining rate of the basins will be approximately 6 in. per hour.
- The modules will be allowed to air dry for 28 days under ambient conditions.
- Nondestructive evaluation of the performance of the module will occur during the drying period. This will include both visual observations and data from moisture/humidity monitors located within the module's walls and floor.
- Clean-up activities and restoration efforts (if warranted) will initially occur after the 28-day drying period. Clean-up activities in future test modules may be included within the drying period if initial testing indicates that a superior outcome is likely.
- After the completion of the drying period, clean-up, and restoration efforts, the modules will have the roof system removed and will then be disassembled and removed to an interior space where an "autopsy" (destructive testing) will be performed. The autopsy will be used to identify the conditions within the systems and materials that are not normally visible or measurable.

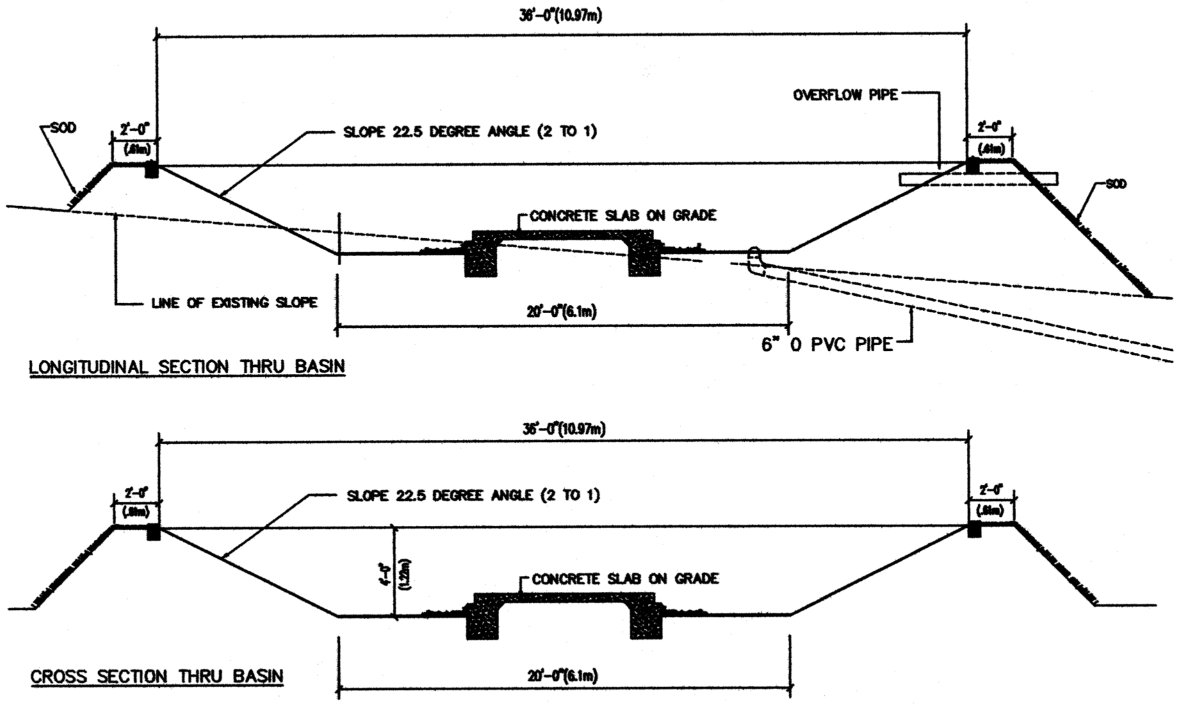

Figure 1a Cross section through test basin with slab-on-grade foundation.

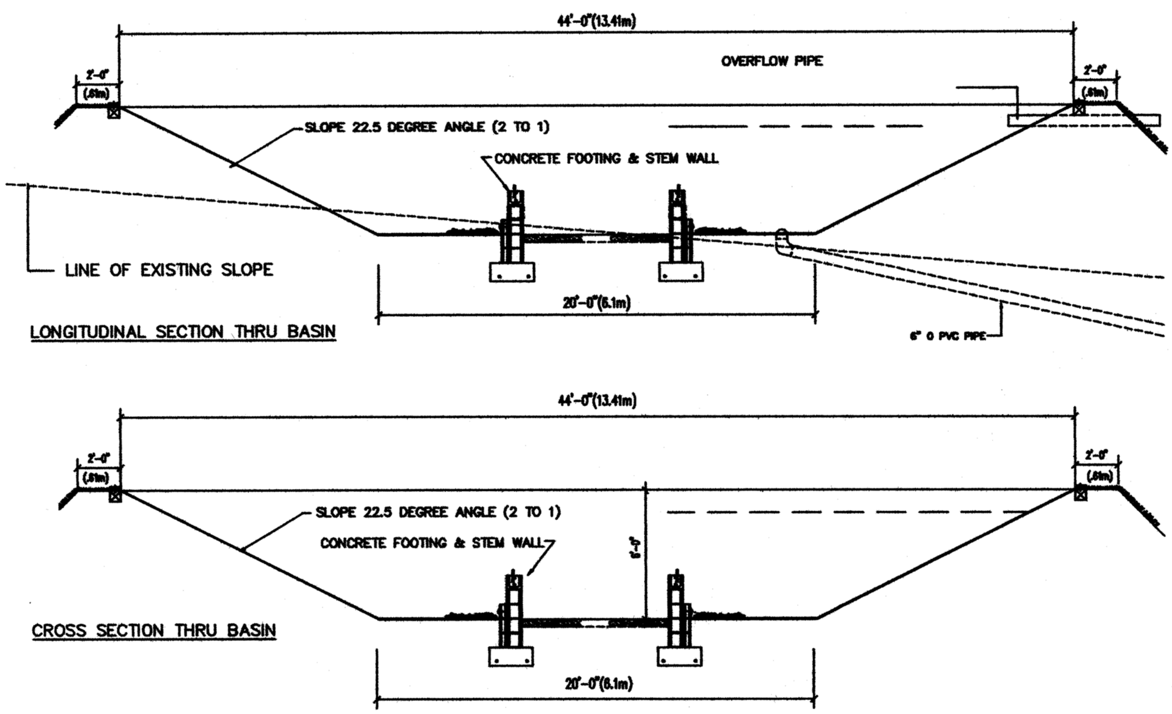

Figure 1b *Cross section through test basin with stem-wall (crawl space) foundation.*

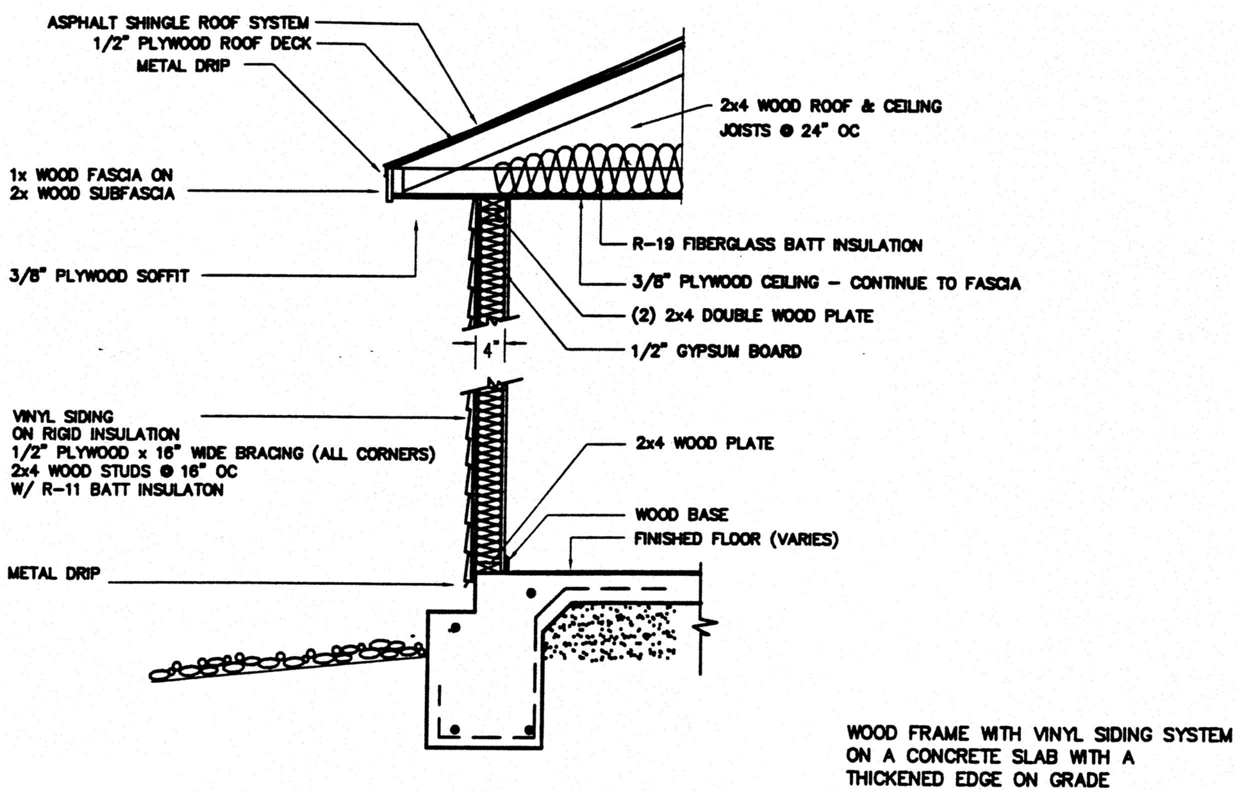

Figure 2a *Details of test module (S-1) of current construction practice with slab-on-grade foundation.*

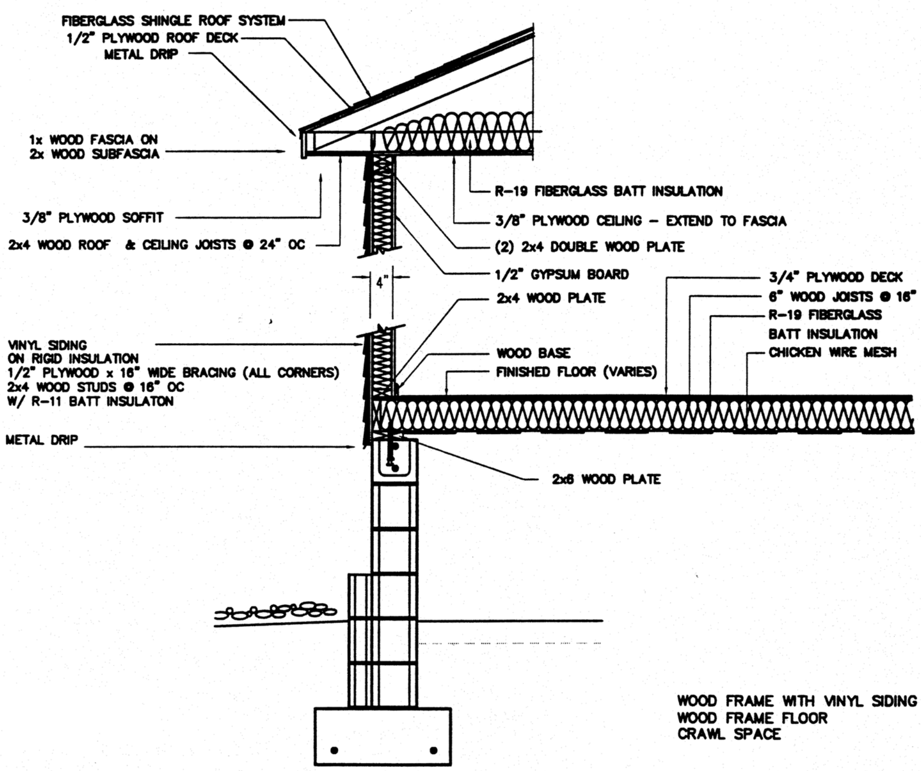

Figure 2b *Details of test module (C-1) of current construction practice with stem-wall (crawl space) foundation.*

TABLE 1a
Evaluation Matrix for the Test Protocol Based on Visual Observations

Building Element Evaluated:				
Date of Flooding	**Prior to Flooding**	**After Flooding**	**Comments**	**Protocol Section or Standard Test Method to be Used**
Visual Observations	Date:	Date:		
General Appearance				Protocol Section 5.8.7[1]
Color				Protocol Section 5.8.8[2]
Texture				Protocol Section 5.8.9[3]
Washability				Protocol Section 5.8.6[4]
Cracking				Protocol Section 5.8.10[5]
Checking				ASTM D660-93
Flaking/Scaling				ASTM D772-86, Protocol Section 5.8.11[6]
Efflorescence				Protocol Section 5.8.12[7]
Biological				Protocol Section 5.8.5[8]
Odors				Protocol Section 5.8.13[9]

[1] Any apparent change in the overall appearance with respect to the appearance prior to flooding shall be observed and documented photographically. All photographs taken prior to and after flooding and restoration will be done with the same lighting and magnification.
[2] The change in color with respect to a reference point (i.e., panels or sections prepared in the same way during construction) shall be observed at 14-day intervals during the drying period. The observations will be made using normal daylight by three individuals with normal eyesight.
[3] Surface macro texture shall be compared to that prior to flood testing. This will be achieved by feeling the surface before, during, and after the drying period. A relative comparison based on the roughness of the surface will be made. This observation will be made by three individuals.
[4] Test elements/components with visible solid deposits and stains shall be cleaned with a bleach/clothes washing detergent solution. Characteristics such as stain discoloration and remaining solid deposits will be noted.
[5] Any observed cracking shall be documented photographically. Cracking characteristics such as length, thickness, and frequency per unit area will be used for comparison.
[6] Development of microstates (those visible with the naked eye) on surfaces of building elements/components after flood testing and during the drying period shall be observed and photographed. The size and/or scale aspect ratio, as well as the number of scales per unit area, will be used as a means for evaluation.
[7] The appearance of white blotchy spots or streaks on the surfaces of building elements/components during the drying process shall be observed and recorded photographically. The ease and completeness of efflorescence removal, using a dilute (5% to10%) muriatic acid or vinegar and water solution, from the building elements/components during the restoration efforts will be noted.
[8] The nature and extent of biological factors, such as bacteria count and mildew growth and coverage, shall be observed, quantified, and documented-based on microscopic counts per unit area.
[9] The building envelope shall be inspected and any persistent or objectionable odors present noted. The inspection will be made by three individuals.

The results of this testing will define a baseline of existing construction practice for comparison with the future module tests involving flood-damage-resistive materials and systems. See Tables 1a and 1b for the planned evaluation format. A set of observations based on this format will be performed and documented prior to flooding to establish the basis of comparison. Observations will also be made and documented following flooding and at 14 and 28 days drying time. Restoration efforts will be made after the drying period, including cleaning with appropriate materials and surface refinishing where applicable. Following the restoration efforts, another set of observations will be made and documented. It is possible for a material/component to "fail" at the end of the drying period but "pass" after restoration is complete. All subjective observations will be based on the consensus of opinion of at least three people. It should be mentioned that a "passing" criteria for an observation or measurement is that the quality/condition of the element or component will be returned to its original state without more than a 10% deviation from its original condition. Some of these criteria remain under consideration and will be further determined after initial testing and evaluation.

Flood-Damage-Resistive Systems Testing and Evaluation. Additional test modules (4-8), constructed using materials and systems that are expected to be flood damage resistant, are being developed. These could include plastic foam insulation, water-damage-resistant gypsum wall board products, vinyl siding and windows, as well as water-damage-resistant doors and windows. The modules will be subjected to testing in the same manner as the baseline modules described above.

Potential Materials and Systems Testing by Industry. As the awareness of this project increases, it is expected that industry may find it desirable to use the test facilities to develop and evaluate their individual products. The potential will exist during the later tests for these firms to join in the process. The costs associated with this testing would be borne by the industrial partner.

Best Practices Guide. At the conclusion of testing, a Best Practices Guide(s) for flood-damage-resistive residential

TABLE 1b
Evaluation Matrix for the Test Protocol Based on Measured Quantities

Building Element Evaluated:				
Date of Flooding Date:	**Prior to Flooding Date:**	**After 28 days drying Date:**	**Comments**	**Protocol Section or Standard Test Method to be Used**
Blistering				ASTM D714-87(1994)
Surface wetability				ASTM D5725-99
Water absorption				ASTM C272-91, D5795-95, D1037-99
Operating force				ANSI/AAMA/NWWDA 101-I.S.2- 97
Dimensional stability				Protocol Section 5.8.2[1]
Thermal Properties				ASTM C1155-95, C1363, C1199, C177, C518, C1114, NFRC (1997)
Creep Deformation				ASTM E1803-99, D6112-97, D2990-95
Peel Strength				ASTM E2004-99, D903-98
Flexural Strength				ASTM D3043-95, E529-94
Tensile Strength				ASTM D1037-99, C474-97, E455-98
Compressive Strength				ASTM D1037-99
Shear Strength				ASTM E564-95
Adhesive				ASTM C1404-98, D906-98, D2339-98, D4680-98, C557-99, D2559-00, D3498-99

[1] The dimensional stability properties to be measured shall be those necessary for the material to be capable of performing the intended function after the flood exposure and drying. For fixed elements/components this may consist of effects such as swelling, shrinkage, or warping of the subject. For moveable elements this may consist of effects to the operation and /or functionality of the subject after exposure. For example, changes in the operating force (the amount of force it takes for the sash to operate) is pertinent to fenestration products.

construction will be prepared for use by homeowners, builders, and building officials. The format and method of information dissemination are still under evaluation.

Task III. Analysis and Modeling

This work is envisioned to begin in 2003. It will provide a computer-based model of flood-damage-resistant systems that will enable the user to predict the moisture levels in the system for selected drying conditions and drying periods. Data will be collected from all test modules as well as the ambient weather conditions during each testing period to assist in validating the simulation model.

Preferred Materials/Systems Drying Rates and Systems Drying Rate Model Validation. Subtasks to be accomplished include the following:

- Analyze and document data from the various test modules.
- Measure and document the critical properties of materials that show promise during flood testing. These would include moisture absorption curves, moisture desorption curves, suction isotherms, liquid diffusivity, water vapor permeability, dimensional changes, drying rates, physical changes (including thermal properties), mold/mildew growth, etc.
- Develop and validate drying models for the construction systems tested.
- Develop a simulation of the drying performances of at least 30 different locations (climates) within the U.S.
- Complete the systems drying model database and format it for use by builders and building officials.

CONCLUSIONS

Research efforts are underway to provide scientific information to guide the design and construction of building envelope systems and components that have the ability to withstand exposure to flooding. Emphasis is being placed on performance issues related to systems and subsystems, such as the impact of wetting and drying on durability and energy efficiency. The following three integrated tasks form the basis of this research:

1. Development of testing protocol and field test plan.
2. Field testing of traditional and flood-damage-resistive-residential systems.
3. Development of computer modeling of system and subsystem performance.

This integrated approach will employ solid building science principles, coupled with material performance, adjusted by real field data to develop a set of flood-damage-resistive, energy-efficient residential envelope systems. The testing protocol and its field test plan counterpart have been developed and rigorously reviewed by authoritative technical scientists and engineers.

It is anticipated that by late 2001, the field testing facilities will be operational and several modules with both conventional and flood-damage-resistant building envelopes will have been tested. Data will be analyzed as outlined on the observation matrix provided in the testing protocol.

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Advisory Team

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