After the Flood

Since people continue to build—and rebuild—their houses in flood prone areas, finding the materials that hold up best after flooding could save energy and money and keep tons of material out of landfills.

by Sherry Livengood and Heshmat Aglan

The extensive flooding that took place last fall in the southeastern United States brought attention once again to a persistent problem. Floods and flooding result in more damage to buildings throughout the United States than any other natural cause. Since 1990, property damage in the United States related to flooding alone is estimated to have exceeded $30 billion, and millions of people have been left homeless. Homeowners are discouraged from constructing new homes in flood-prone areas, but where existing homes are flooded and must be repaired, the damage from future flooding will be minimized through the use of materials and methods for renovation that resist flood damage.

To identify the materials and methods that floodproof a house, the Residential Group of Oak Ridge National Laboratory (ORNL)'s Buildings Technology Center, in conjunction with Tuskegee University's College of Engineering, Architecture, and Physical Sciences, is flooding and then testing typical residential building envelopes.

Because reproducing flood conditions in actual residential structures would be extremely expensive and impractical, we instead designed small prototypical test structures—8 ft x 8 ft modules placed in outdoor basins in Tuskegee, Alabama (see photo above and Figures 1 and 2). These test modules simulate the materials and systems used in full-sized residential structures as well as representative flooding and real world drying conditions, while minimizing the cost of materials and construction. We built one slab-on-grade test module and one module with a crawlspace for each series of tests. Two series of tests have been conducted, and a third is underway.

ORNL

Minimizing Flood Damage the Next Time

The Federal Emergency Management Agency (FEMA) defines flood-resistance as the ability of materials, components, and systems to withstand direct and prolonged contact with flood water without sustaining any degradation that requires more than cosmetic repair to restore it to its original condition. We essentially adopted this standard for our experiments. Flood-resistance includes both physical and human health factors. We tested the resistance of our test modules to physical degradation that results from the wetting and drying cycle associated with flooding. Our testing did not address the structural impact on the envelope of externally applied hydrostatic pressures. However, we limited flood depth to 2 ft above floor level, which will apply a pressure that is within the strength capabilities of typical wood frame construction.

Along with testing for physical degradation, we tested for degradation resulting from biological invasion, such as the uncontrollable growth of mold, mildew, or rot. And we defined contamination-resistance as the ability of a material to be cleaned of contaminants through surface washing and refinishing.

We tested a variety of materials and methods. For example, the test modules were built with several different types of sheathing: oriented strand board (OSB), plywood, foam sheathing (with metal straps to prevent racking), and a sheathing material from US Gypsum (USG) called Fiberock.

A variety of flood conditions can occur. Riverine (fresh-water) flooding can cause different sets of problems for residential structures than coastal (salt-water) flooding. Whether the flooding is urban or rural can affect the type and amounts of biological and chemical pollutants in the floodwater. Air temperatures and other climatic conditions—such as ice and wind—affect the type of flood damage as well as the length of time needed for the structure to dry. The depth of flooding is also of critical importance to how well a structure and its contents can survive a flood.

The initial tests at Tuskegee examined relatively low-level fresh-water flooding where especially noxious biological and chemical contaminants were not present.

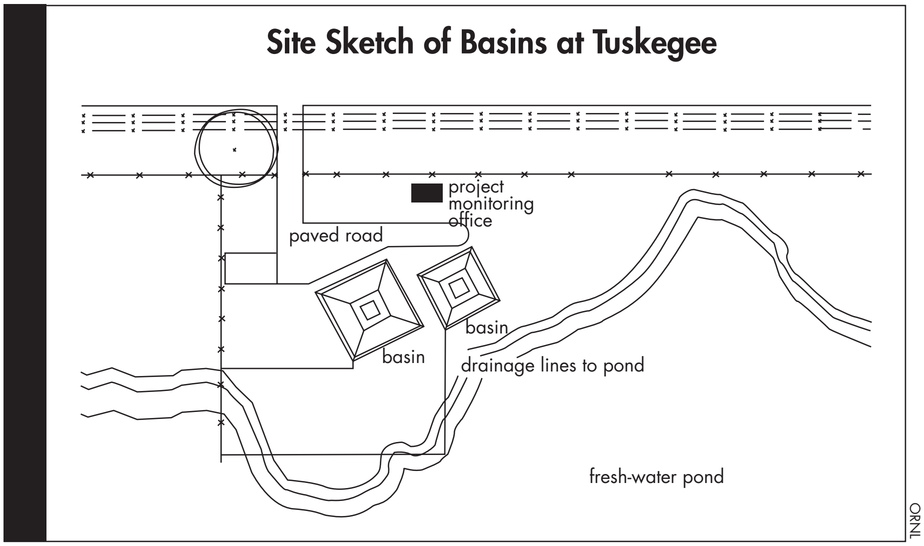


Figure 1. Two basins, one for a crawlspace module and the other for a slab-on-grade module, were flooded with pond water to test building envelopes exposed to flooding.

Table 1. Timeline of Testing Protocol

Day -7	Completion of construction & finishing
Day -4	Initiation of monitoring instruments
Day 0	Flooding of basins/modules
Day +3	Draining of flood basins (72 hours)
Day +8	Re-entry and opening doors/windows
Day +8	Remove mud, caprets; rinse surfaces
Day +10	Sanitize surfaces and continue drying
Day +30	End of measurements this module

Temperatures were above freezing so that ice was not a factor. Furthermore, the tests addressed only water damage, not structural damage resulting from high winds or fast currents. In flash floods, the water usually rises and falls quite rapidly. Many materials can sustain brief wetting without permanent damage. However, we decided that to represent a wider variety of flood conditions and provide a more stringent test of materials, we would leave the structure submerged for three days, a reasonable representation of flooding in the United States.

Using water pumped from a nearby rural agricultural lake, the test basins were filled to 2 ft above the floor level of the simulated houses. During the periods of flooding, draining, and drying, the test modules were closely monitored and observed (see Table 1). After draining, the structures were allowed to dry in the natural environment for 30 days. On day 8, we opened the doors and windows, removed mud and the carpeting, and rinsed the walls of the test houses. Two days later, on day 10, we sanitized the surfaces by spraying them with a solution of water, household bleach, and trisodium phosphate. We observed, measured, and recorded the physical properties and performance characteristics of the materials. At the conclusion of the 30-day drying period, we performed tests to evaluate the effectiveness of cleaning and restoring the materials and systems used in the houses. In addition, we "autopsied" the materials used in the test modules to determine their final physical characteristics in areas that are not normally subject to inspection.

Conventional Construction

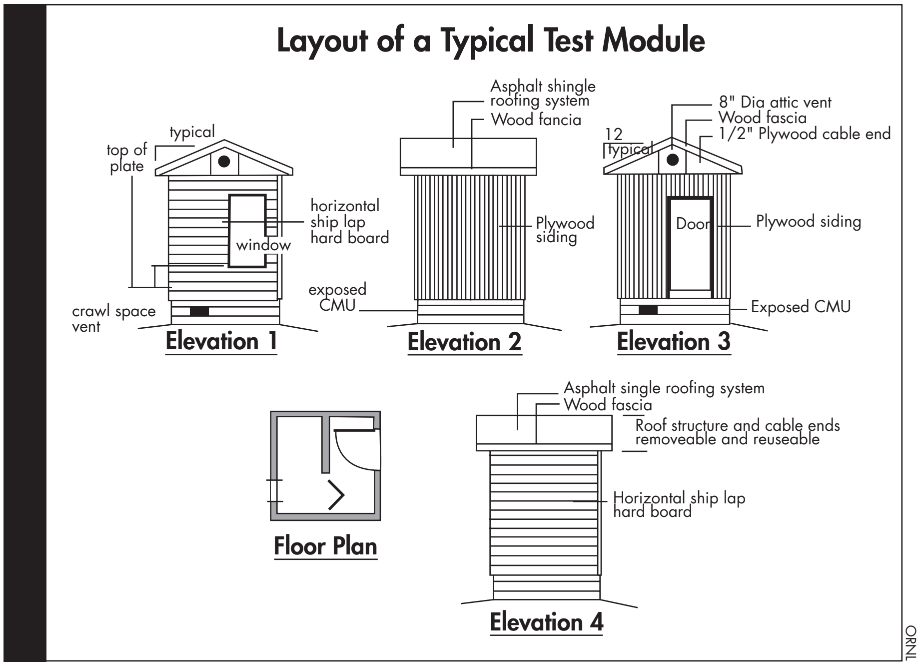
In the first tests (November 2001), two test modules were built with typical home construction materials and methods. One module had a crawlspace and the other was built slab-on-grade. One room of the crawlspace module was finished with ceramic tile on the floors and walls. The floor joists in the crawlspace module were 2 x 6s with 3/4-inch plywood subflooring. In the slab-on-grade module, we installed vinyl wall covering in one room, and one of the concrete floors was sealed and left bare. Carpeting was applied on the floors of rooms in both modules.

Half the sides of the two modules were sheathed with oriented strand board (OSB) and half with plywood. Hardboard lap and plywood (T-111) siding were applied to the exterior sheathing. The exterior walls were insulated with unfaced fiberglass batt insulation between the 2 x 4 stud walls. The interior wall finish for both test modules was standard gypsum wallboard. These walls were painted with two coats of either flat latex, or latex semigloss enamel paint. Windows were double pane aluminum framed with white baked-enamel finishes. One of the exterior doors was made of steel and one was made of exterior-grade solid wood. Typical traditional in-wall electrical wiring (not powered) was installed, with duplex outlets installed at normal height (below the flood level). The ceilings were made with gypsum board and the attic and roofing were made with 2 x 4 framing, plywood decking, R-11 fiberglass insulation, and asphalt shingles.

In order to observe the flooding and drying process, we placed moisture sensors at various elevations in wall studs, flooring, and joists (see Figure 3). We took measurements every 20 minutes during flooding and every three hours after the test modules were drained. Wall framing dried to preflood moisture levels in 20 to 30 days. We also measured relative humidity (RH) inside the test modules and inside the walls. The interior RH went up to approximately 85% during flooding and remained at that level until the doors and windows were opened on day 8. The RH returned gradually to levels that reflected outdoor conditions.

Inspection on day 8, when the modules were opened, the carpet removed, and the surfaces washed, revealed staining on the exterior walls below the water level, some warping of the vertical plywood siding, and vertical cracks in the exterior corner molding. The wooden door required about 10 lb of force to open (it stuck slightly), and it was discolored below water level.

Upon entering the test modules, we were welcomed by a strong musty smell. The carpeted areas were still fully saturated and slightly muddy. The hollow-



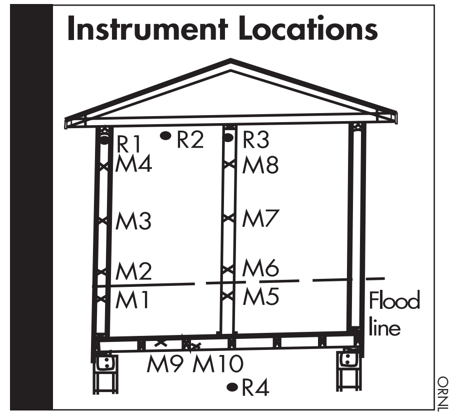


Figure 2. *(above)* The test modules allowed us to test a number of building materials and systems for flood damage resistance. **Figure 3.** *(top right)* M1–10 are moisture sensors embedded in the wood framing and protected from direct contact with water by silicone caulk. R1–4 are temperature and relative humidity sensors. R4 was installed after the floodwater was drained.

Table 2. Flexural Strength of Gypsum Board for Module 1

Exterior Wall	
Above Water	**Below Water**
3.2 MPa	1.64MPa
Interior Wall	
Above Water	**Below Water**
3.68MPa	3.56MPa

core interior doors were stained and split at the bottom. There was a waterline on the gypsum board walls at approximately 2 ft above the floor level. The sealed concrete floor did not appear damaged. The paper drywall tape was peeling off the wall at joints and corners below water level. The paint on the walls was blistering below water level. The latex semigloss enamel appeared to fare better than the flat latex. The ceramic tiles on the floor and walls were in good condition, though the grout had been eroded on the flooring and was discolored throughout.

Upon entry on day 8, no mold was observed (probably because this occurred in December, with cool and dry external conditions). However, beginning on day 16, we observed dark-yellowish mold spots. Some flood damage repair manuals recommend making holes in the bottom of walls so that any water in the wall cavities behind the gypsum board can drain out. Therefore, on day 8, we punched holes through the gypsum board at the bottom of the walls and near the top of the floor plates. No water was observed draining from the wall cavities. However, the batt insulation in the exterior walls was still soggy.

As anticipated, the paper-faced gypsum wallboard remained unserviceable where it was installed on the inside of fiberglass-insulated exterior walls. The batt insulation appeared to act like a sponge and held water. However, on interior partitions, where there was no insulation in the wall cavity, the gypsum wallboard was in good enough condition to be lightly sanded, resurfaced, painted, and returned to use (see Figures 4 and 5). Where there was no insulation in the wall cavity, the area drained and dried more rapidly. Subsequent mechanical properties testing of materials revealed that the gypsum board on the interior walls did not lose significant strength (see Table 2).

Flood Damage Resistant Construction

We attempted to learn from the first two test modules which materials and systems resisted flood damage and which did not. In the second tests (April 2002), we installed vinyl siding and fiber cement lap on the exterior, and foam-filled metal and foam-filled fiberglass exterior doors. On the interior, we installed a wood laminate hollow-core door and a six-panel, solid-wood interior door. Because the batt insulation contributed significantly to the degradation of the gypsum board interior walls, we used sprayed polyurethane foam (SPUF) in the exterior wall cavities in place of the batt insulation. Because SPUF is not water absorbent, it minimizes the amount of water that enters the wall cavity, allowing the walls to dry faster and more completely within the test period. We installed USG's Fiberock interior wallboard to see if it was more damage resistant than the gypsum wallboard. And we installed simulated-wood flooring.

On day 8 we opened, entered, and inspected the test modules. The exterior vinyl siding and fiber cement lap siding were mildly stained, but otherwise in good condition. (Washing the surface later removed the stains.) The foam-filled metal and the foam-filled fiberglass exterior doors were also stained, but otherwise in good condition. The wood laminate hollow-core interior door was delaminated, warped, and badly stained, and it was determined to be beyond repair. The six-panel solid-wood panel interior door was also slightly warped and showed water staining. While it could be

Because reproducing flood conditions in actual houses was not practical, we made small prototype test structures.

repaired, the cost of the effort would probably exceed the cost of replacement.

The interiors smelled strongly musty and the walls showed significant mold growth, most of it concentrated in a 20-inch band above the waterline. This was observed in April, when ambient conditions (temperature and RH) were ideal for mold development. Walls painted with latex semigloss enamel were slightly moldier than walls painted with flat latex. Mud and dirt lined all the floors and walls. Joint compound and tape were peeling off the interior walls below the water level. All surfaces below the water level were stained and discolored. Again, we drilled drainage holes at the bottom of the walls and found no water inside the walls. The SPUF was not saturated. We removed mud and debris and took out one of the simulated-wood floors to be cleaned and dried. We used water from a garden hose to rinse off interior and exterior walls, floors, doors, and windows.

On day 10 we sprayed and washed the interior and exterior surfaces with a solution of 25% household bleach, 5% trisodium phosphate, and 70% water. After the surfaces were cleaned and sanitized, no visible mold growth returned. Autopsies of the interior of walls showed no mold development. After 30 days of drying, wall surfaces were sanded and joints were repaired, resurfaced with joint compound, and caulked where there were crevices. Then two coats of paint were applied. The exterior door was restored with one coat of paint. These restoration efforts were judged to have returned the materials in question to preflood appearance and condition.

In the second tests, we installed a video camera to observe how and where floodwater entered the test modules. The cameras showed that in the slab on grade module, water entered initially under (not through) the exterior walls and not around the door. Water appeared to be entering this test module under the wall plate. Additional water appeared to have entered around the door and the window later during flooding, when water in the basin rose to the levels of these openings. In the crawlspace test module, the cameras showed water first entering through joints in the subflooring, followed by the interface between the wall plate and the floor.

Flood Proofing Homes

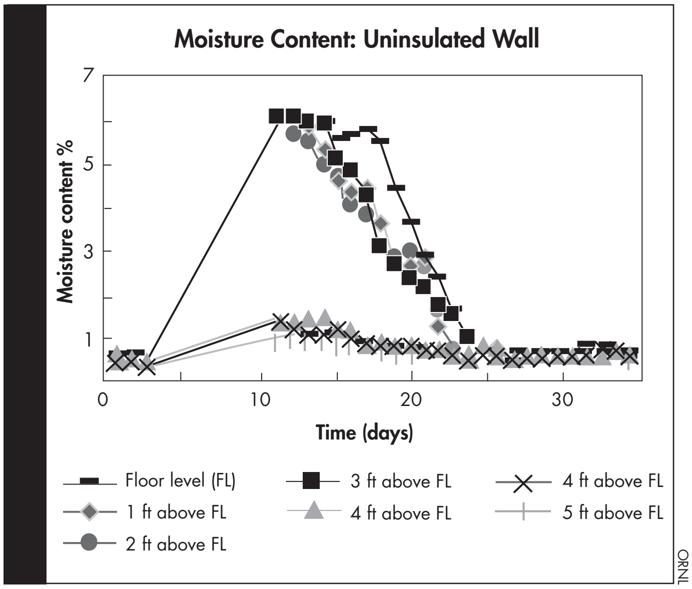
Several preliminary observations can be made. In the tests at Tuskegee, punching holes in the gypsum board walls did not help to drain the wall cavities and it did damage the salvageable gypsum board walls, thus increasing the repair effort or requiring them to be replaced. Unless there is strong reason to believe that water remains in the wall cavities, punching holes does not appear to be beneficial.

When restoring their flood-damaged home, homeowners should consider replacing the batt insulation in the exterior walls with SPUF, which does not retain water and thus does not contribute significantly to the deterioration of the gypsum board walls. SPUF also provides a higher R-value (approximately R-18 versus R-11) and a better air seal than batt insulation. While it is more costly than batt insulation, the reduced costs of repairs resulting from any future floods would more than offset the higher initial costs. In the meantime, the energy performance of the envelope will be enhanced.

Surprising as it sounds, if the gypsum board walls can be allowed to dry fairly quickly and if nothing physically damages the walls, they can be sanitized, sanded, repaired at the joints, repainted, and returned to use. Two products made by USG—Fiberock sheathing and wallboard—were also tested as exterior sheathing and as interior wallboard. These products were sanitized, sanded, repainted, and restored to preflood condition. The Fiberock sheathing is listed as water resistant (WR) and it supported little if any mold growth when used as sheathing and as interior wallboard. The Fiberock wallboard supported slightly more mold growth than the standard paper-faced gypsum wallboard. Although it is heavier and more expensive than conventional gypsum products, the Fiberock sheathing, used as wallboard, may be beneficial in areas where mold growth is a problem even under nonflood conditions.

Vinyl siding and fiber cement siding both appear to withstand flood conditions better than plywood siding, and we consider them to be flood damage resistant from our testing thus far. Vinyl and aluminum window frames, as well as insulated steel or fiberglass doors, were restored to preflood condition with minimal effort.

Sealed concrete floors in slab-on-grade houses appear to stand up well, as do ceramic floor and wall tile in either slab-on-grade or crawlspace houses. The



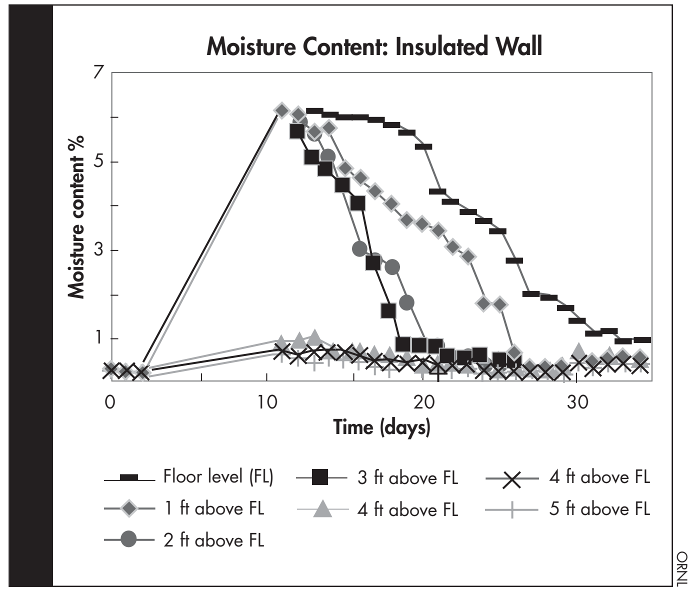


Figure 4. *(left)* This shows the moisture content versus time for the gypsum board on the uninsulated interior wall of a test module. The entire wall (top to bottom) dried within 25 days. **Figure 5.** *(right)* This shows the moisture content versus time for the gypsum board on the interior of an insulated outside wall. Notice how the floor level and 1 ft above floor level retains moisture for 5 to 10 days beyond the upper portion of the wall. This is due to moisture retained by the fiberglass insulation.

carpeting tested so far does not withstand flooding very well and appears to require removal to promote drying within the home.The simulated wood flooring warped and created open joints when left in place after the flood.This flooring, when removed, washed, and stacked to dry had much less warping. However, some of the tongue-and-groove joints were damaged in the removal process. It is not yet clear if this type of material would be salvageable after being subjected to flooding.

Guidelines for energy-efficient construction usually recommend that builders seal between the wall plates and the floor, although this has not usually been standard industry practice. Since the area between a concrete slab and the wall plate is a major route for floodwater, sealing this joint has implications not only for flood-resistance, but for the reduction of air infiltration as well (see "Testing Air Sealing Techniques," p. 36). If floodwater can easily enter the structure at this point, how much more easily could outside air enter the structure throughout its lifetime? Knowing where most of the floodwater enters the structure could make it easier to minimize damage from future floods.

Because we were attempting to approximate conventional construction, no sealant was applied between the slab floor and the wall plate. After a flood, the home renovator would probably not remove the exterior wall studs, and therefore it would be difficult to seal between the floor and wall under the plates. However, it appears that there will be some benefit (it will limit air infiltration, at least) to running a bead of water-resistant (silicone) sealant at the joint where the wall plates and the floor meet before replacing the flood-damaged gypsum board walls.

More Testing

The third set of test modules is testing the hypothesis that silicone sealant helps to prevent flood damage.Various other materials for siding, sheathing, insulation, floors, walls, and floor and wall finishes will also be tested, as will additional carpet products (so far, the carpets have always had to be replaced). Future test modules will examine the impact of various methods of construction as well. Dry floodproofing (preventing the entry of any water into the building envelope) will be attempted in one of the next tests. When the most promising materials and systems have been determined, they will also be subjected to more severe flood-water contaminants, such as fuel oil, sewerage, or salt water.

Based on what is learned from these field tests, ORNL researchers will develop recommendations for improving the flood-damage-resistance properties of residential envelope systems. As a result, homeowners in flood-prone areas will have the information they need to restore their houses after the flood, so that the homes are more resistant to damage from future floods. In the process, measures put in place to minimize flood damage will also save energy and lower utility bills.

Sherry E. Livengood is a research engineer at the Buildings Technology Center of Oak Ridge National Laboratory in Oak Ridge, Tennessee. Heshmat Aglan is professor of mechanical engineering in the College of Engineering, Architecture and Physical Sciences at Tuskegee University in Tuskegee, Alabama.

This article would not have been possible without the significant contributions of Robert Wendt of Oak Ridge National Laboratory and Timothy Barrows at Tuskegee University.

This research is being funded through the Federal Emergency Management Agency, the U.S. Department of Energy, and the U.S. Department of Housing and Urban Development.