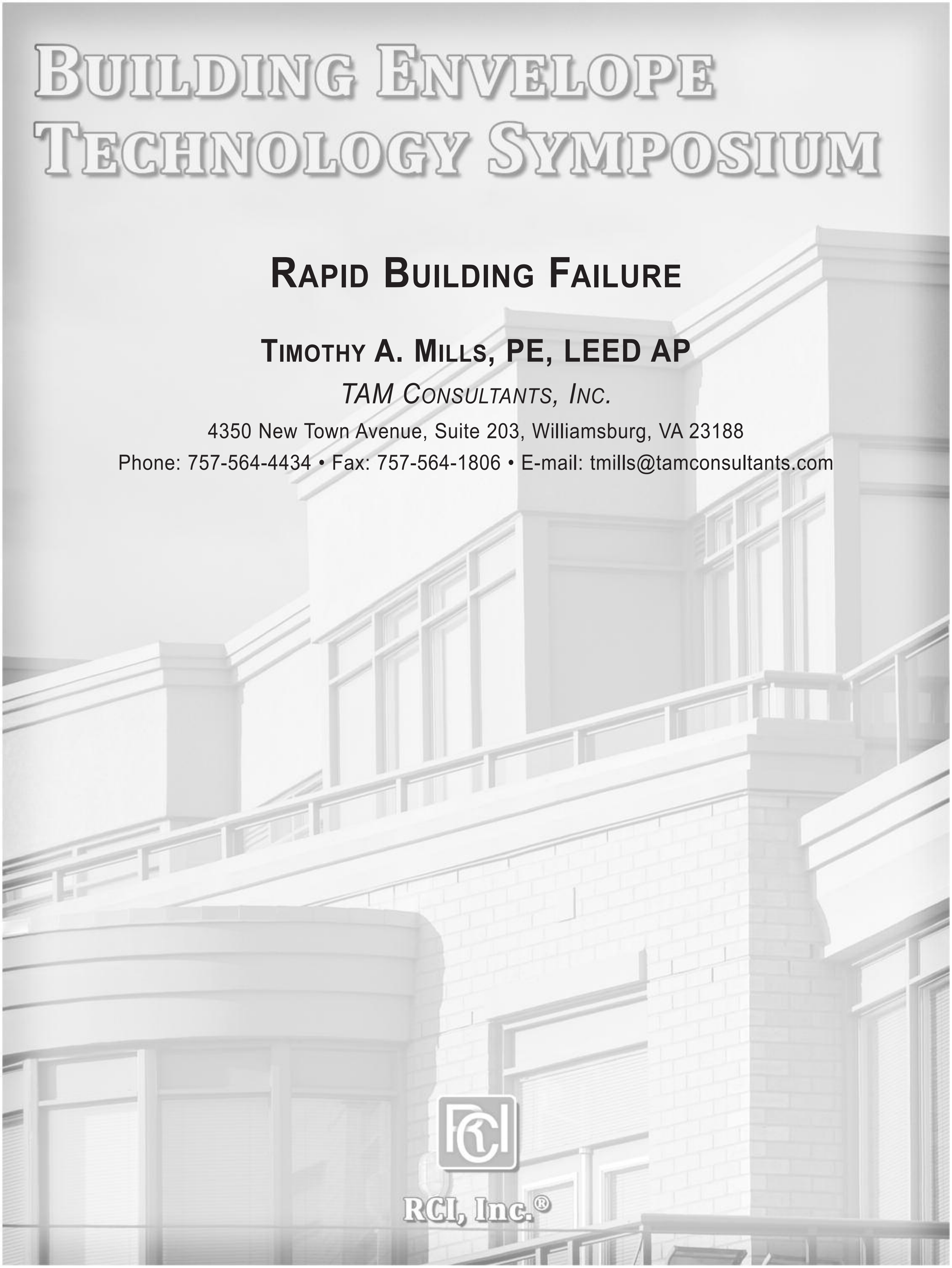

BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

RAPID BUILDING FAILURE

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ABSTRACT

This presentation will provide a case study of how an experienced project team, through a series of design, administration, and construction decisions, managed to create a world-class health club and spa facility, but not before working through disastrous and costly building issues. The presenter will describe the original design, changes that were made in the submittal process, method of the original construction, initial discovery of problems during the punch-list phase, investigation and repair options that were presented, and finally, the repair and construction techniques used to fix the building. Lessons learned include good design and good construction procedures and understanding water vapor transmission and condensation in building assemblies.

SPEAKER

TIMOTHY A. MILLS, PE, LEED AP — TAM CONSULTANTS, INC.

Timothy Mills founded TAM Consultants, which specializes in providing building enclosure and air barrier consulting, forensic engineering, property inspections, structural engineering, and design and project management services for the built environment. Mills has a bachelor of science degree in engineering from Brooklyn Polytechnic Institute of New York. He is a licensed professional engineer, a LEED AP, and a licensed field auditor for the Air Barrier Association of America (ABAA). Mr. Mills's 27 years of experience cover a wide range of public and private projects of all sizes. Project types include commercial, federal, municipal, educational, institutional, single- and multifamily residential, historical, industrial and manufacturing facilities, laboratory, parking, green buildings, and retirement facilities. Projects range in value from small to in excess of $300 million.

RAPID BUILDING FAILURE

ABSTRACT

Just prior to the completion of this high-end senior living health club facility, widespread and massive condensation problems resulted in building damage and mold infestation. The owner was eventually forced to shut down portions of the brand-new facility and embark on an extensive repair that involved removing large portions of the roof, building insulation, and vapor barriers. The repairs implemented good design, detailing, and construction practices that had been lacking during the original project. The work included installing sheet and fluid-applied vapor barriers, spray polyurethane foam, and new roofing. The entire project team worked through the costly and reputation-damaging problems and ultimately provided the owner with a state-of-the-art facility. This paper will describe and demonstrate the detailing and specifications for the original design, changes that were made in the submittal process, method of the original construction, initial discovery of problems during the punch-list phase, investigation and repair options that were presented, and finally the repair and construction techniques used to rehabilitate the building. Additionally, this paper will provide lessons learned that can be applied to good design, good construction procedures, understanding water vapor transmission and condensation in building assemblies, and how a project team worked together to solve the problems.

INTRODUCTION

This case study will examine the design and construction of a high-end senior living health club and spa facility, which includes an indoor swimming pool and hot tub as part of a larger, two-story building with exercise rooms and community areas.

A few types of buildings offer great opportunities and serve as examples for learning about the importance of designing and constructing airtight and, in some cases, vaportight building enclosures. These include hotels, motels, museums, hospitals, refrigerated buildings, high-humidity manufacturing plants, and natatoriums (indoor swimming pools). Natatoriums are the best examples worthy of study. The reason is that these buildings are plentiful throughout North America; and due to high internal temperatures and relative humidity, these buildings push the limits of building materials and common design and construction techniques. Studying buildings that must perform in an extreme environment allows us to bring new knowledge to all building types.

With all that has been written and presented about the proper design and construction of natatoriums, one would expect that the design and construction industry has figured out these facilities and building failures would be a thing of the past. Unfortunately, all too often, standard, current practices are yielding the same poor results again and again, to the point where building failure is common. Sometimes building failure occurs so fast that the signs of failure show up before construction is even complete. This paper presents an example of rapid failure.

ORIGINAL DESIGN AND CONSTRUCTION

Natatorium facilities offer special challenges and can be very demanding on building assemblies, primarily because of high indoor temperatures and high relative humidity. A well-designed facility includes a pool room with architectural and mechanical systems that control room temperature and humidity levels, water temperature, and room pressurization. In multiuse buildings, there is a need to maintain some degree of relative negative pressurization among the pool room and the remaining portions of the building to avoid humid pool-room air migration and objectionable chlorine (or bromine) odors from infiltrating other parts of the building while maintaining an overall pressurized building relative to the exterior.

Water vapor naturally moves from areas of high relative humidity (high vapor pressure) to areas of low relative humidity (low vapor pressure) and can readily diffuse through porous (permeable) building materials such as gypsum board, paint, brick, wood, and CMU. Water vapor will not readily move though a vapor barrier (defined as a class I vapor retarder, a material that is vapor impermeable and has a permeance of 0.1 or less). Airborne water vapor will always condense if it comes in contact with a portion of an assembly that is cold enough (i.e., below the dew point temperature). This condensation can lead to steel corrosion, efflorescence on masonry, saturation, mold, and rot in wood and gypsum products. In natatoriums, this "vapor drive" is almost always from the interior of the pool space to the exterior of the building or to adjacent nonpool spaces. This fact requires constructing a well-detailed and positioned vapor barrier as a critical component. The barrier should be placed on the warm (pool) side of the assembly to prevent the water vapor in the moisture-laden pool room air from coming in contact with colder building elements during the winter months. These cold building elements are usually towards the exterior of the enclosure assemblies; but care must also be given to materials that pass through insulation, causing thermal shorts in the enclosure.

In addition to vapor diffusion, moisture can more easily be carried into wall and roof assemblies via moving air. Moisture in an air stream will condense as soon as the air stream contacts a surface that is below the dew point of the air. The amount of moisture transported by air movement is much greater than that transported by vapor diffusion alone (ten to 100 times as much). Therefore, an air- and vaportight air/vapor barrier, as well as negative operating pressure are critical to the performance of natatoriums.

The highly experienced design team in this case study called for a pool water temperature of 84°F with a pool room temperature no more than two degrees above water temperature. A larger difference in the temperature settings would cause user discomfort due to excessive water evaporation from the human skin. Relative humidity was designed to be maintained between 50% and 60% RH. This design results in a high dew point temperature (the temperature when water vapor condenses into liquid water) of between 65° and 70°F (which is

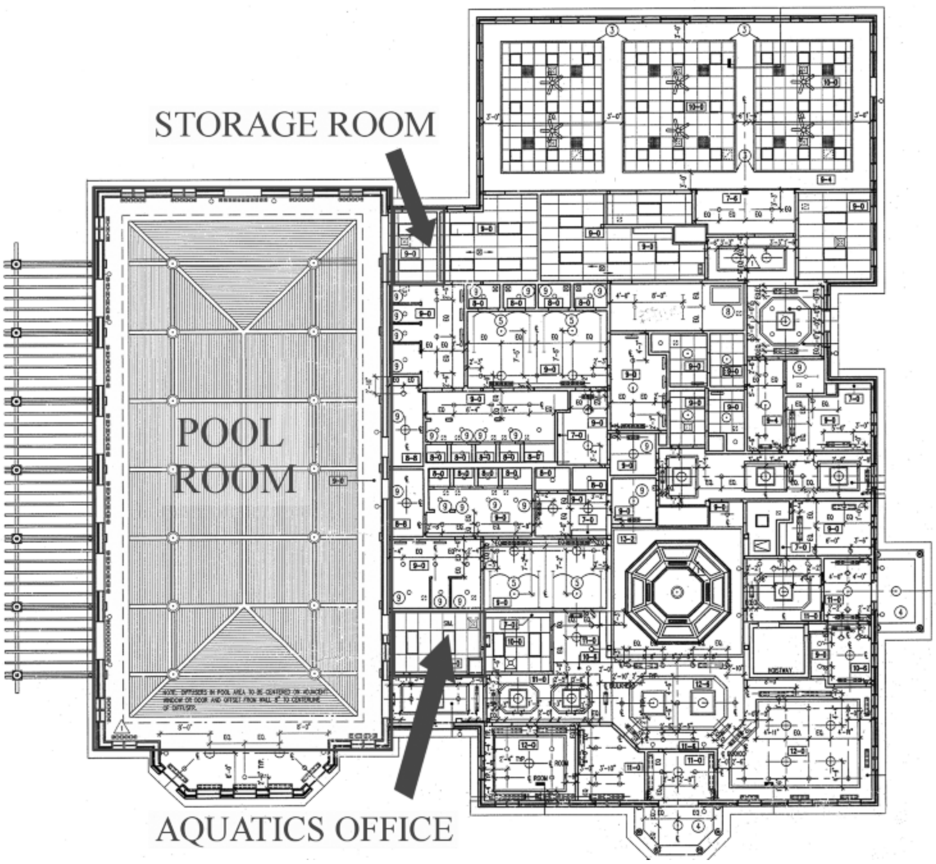
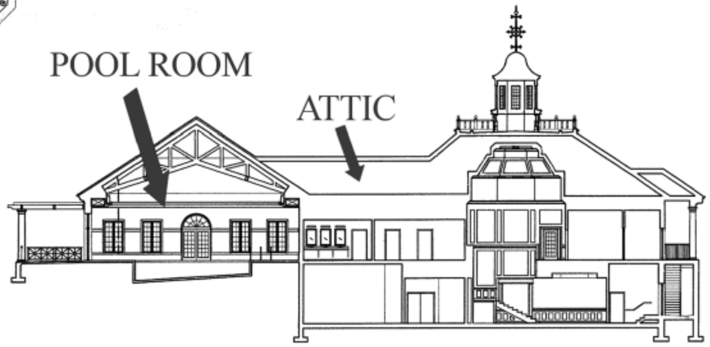


Figure 1 – Reflected ceiling plan with delineation of pool spaces, including the aquatics office and equipment storage room.

Figure 2 – Building cross section with pool room on left and two-story building on right.



not uncommon for pool rooms) and a large vapor drive from the interior of the pool room towards the exterior. Therefore, an air/vapor barrier installed in an airtight fashion was called for on the pool room (warm) side of the enclosure. The facility is located in the southern portion of Climate Zone 4, resulting in fairly mild winters with relatively short periods of below-freezing weather. However, with a dew point of 70°, it isn't hard to imagine that even on a mild winter night, dew point temperatures in the enclosure assemblies can easily occur.

In addition to the large pool room, the pool spaces also included an adjacent equipment storage room and an aquatics office (*Figure 1*). The pump room was located in the basement, and the ducted pool HVAC equipment was located in a roof well above the adjacent locker-room spaces (*Figure 2*).

The pool room portion of the building was designed and constructed with load-bearing masonry cavity walls and heavy timber roof trusses (*Figures 3* and *4*). The adjacent nonpool spaces had a conventional wood-truss system on a steel frame with asphalt shingle roofing as well as precast concrete plank structure with insulated EPDM single-ply roofing. The adjacent construction included attic spaces that abut

Figure 3 – View of original pool building roof structure under construction with truss protection wrap partially removed.

the slope of the pool room roof assembly.

The design of the pool room roof assembly included heavy timber Glu-Lam trusses bearing on the masonry walls with 2-in x 12-in dimensional lumber rafters spanning between the trusses (perpendicular to the roof slope) with plywood roof sheathing, felt paper, and architectural-grade fiberglass roofing shingles. The design also called for a compact roof assembly including an interior ceiling finish of natural beveled cedar-board siding over 2-in x 4-in furring strips over a polyethylene vapor barrier with fiberglass batt insulation placed between the rafters. This compact roof assembly was ventilated with continuous slotted soffit vents and a continuous ridge vent (*Figures 5* and *6*).

Exterior walls included a brick veneer, an air space, rigid polystyrene insulation, a CMU backup wall with a dampproof coating, metal hat channels, a polyethylene sheet vapor barrier, and gypsum drywall with an acrylic latex paint coating. The demising wall between the natatorium and the rest of the building was CMU with metal hat channels, a polyethylene-sheet vapor barrier, and painted gypsum drywall toward the pool side of the wall.


Figure 4 – View of the pool roof heavy-timber trusses and cedar-ceiling finish.

The original design included limited details, although the building sections and details called for a vapor barrier in the walls and roof assemblies at the correct location in most places, i.e., on the warm pool side of the assembly, although the vapor barrier was shown on the wrong side of the demising wall between the pool room and locker rooms. A less-than-robust 6-mil polyethylene sheet was called for (ASTM D4397-09, *Standard Specification for Polyethylene Sheeting for Construction, Industrial, and Agricultural Applications*). Included in the vapor-retarder specification section were generic requirements such as the following:

- "Extend retarder to edges of areas, secure with adhesives or other anchor system, cover voids, including loose-fiber insulation."
- "Seal vertical joints in retarder over framing by lapping not less than two wall studs. Fasten to framing at top, end, and bottom edges; perimeter of wall openings; and lap joints.

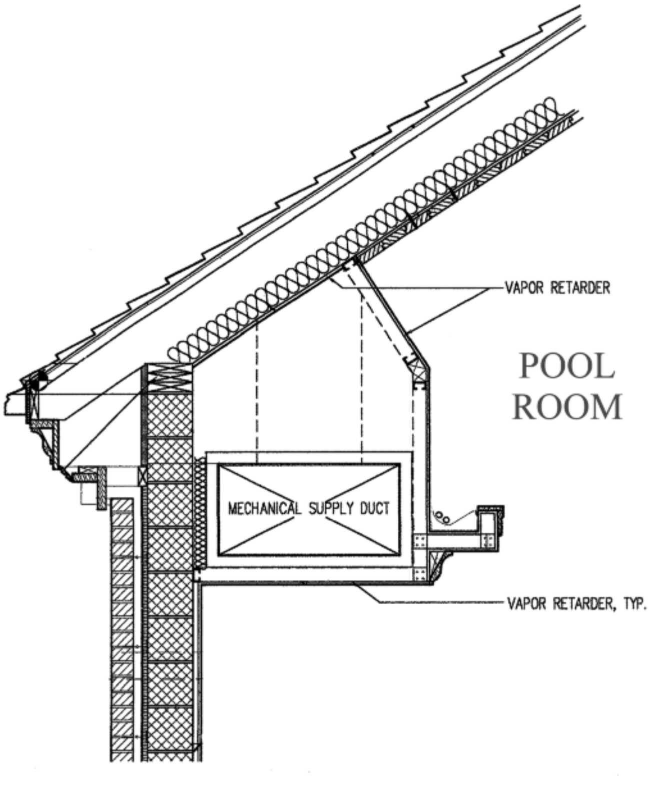


Figure 6 – Original pool room roof/wall intersection and vapor barrier locations.

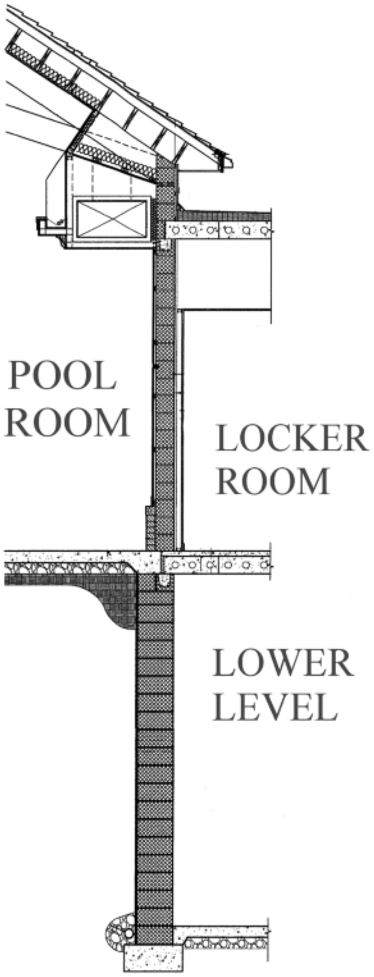


Figure 5 – Original wall section at the demising wall separating the pool room from the adjacent locker rooms and lower level spaces.

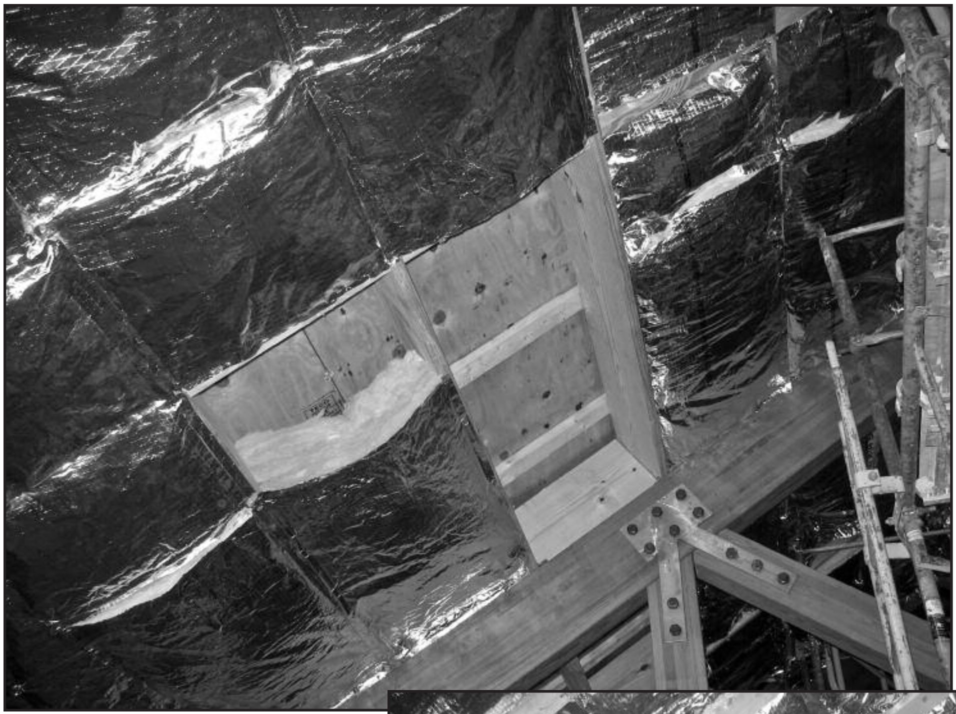


Figure 7 – Installation of the original roof insulation and FSK “vapor barrier.”

Figure 8 – Roof assembly under construction with Glu-Lam trusses and ceiling furring strips shown over FSK “vapor barrier.”

Space fasteners 16 inches o.c.”

- “Seal overlapping joints with adhesives or vapor retarder tape according to manufacturer’s instructions.”
- “Attach retarder to substrates with mechanical fasteners or adhesives as recommended by manufacturer.”
- “Seal joints caused by pipes, conduits, electrical boxes, and similar items penetrating retarder with vapor retarder tape to create an airtight seal between penetrating objects and retarder.”
- “Repair any tears or punctures in retarder immediately with vapor retarder tape or another layer of vapor retarder.”

One could debate that the design and level of detailing are perhaps suitable for a residence or an office building in climate zones 4 or 5 but are not nearly robust enough for a pool facility, and we would agree. A facility such as this requires extra attention and a more deliberate approach to detailing and communicating design intent due to the demanding nature of the use.

During construction, the design firm of record was beyond its capacity to administer the project, and it subcontracted its construction administration and shop drawing review obligations, including site visits, to a third-party construction management company. The owners hired an owner’s representative to assist in coordinating their obligation in the project. The architect’s third-party administrator performed the typical twice-per-month visits during construction to review the work as it progressed to see that the construction generally met the intent of the design.

During the course of the construction-submittal process, the general contractors’ insulation subcontractor, who also had responsibility to install the vapor barrier, submitted a substitution requesting that the polyethylene vapor barrier in the roof assembly be deleted and that it be replaced by an FSK (foil-scrim-kraft) backing on the roof/ceiling fiberglass batt insulation. The substitution was “approved as noted” by the architect’s representative, who noted, “In areas where foil forms vapor retarder, all joints must be taped. . . .” During the course of the work, the contractor also asked for further clarification through the RFI (request for information) process, and the architect's representative clarified and wrote, "The foil side of the FSK insulation, if properly taped and sealed, will act as the required vapor barrier." (See *Figures 7* and *8*).

To expect an air- and vaportight assembly from an FSK product in this application is almost an impossible task. The less-than-robust original design was rendered less so with the approved change request. When the owner's representative questioned the installation, he was assured by the construction manager that the contractor and architect were "on the same page" and the work would be installed properly.

Figure 9 – In the walls, the polyethylene vapor barrier was not taped and sealed at all joints and laps.

The ceiling FSK "vapor barrier" was taped (with metal foil tape) to the bare CMU at the top course at the perimeter of the bearing CMU walls.

On the walls, the vapor barrier installer placed the 6-mil polyethylene vapor barrier over hat channels that were secured to the load-bearing CMU walls. This was covered with painted gypsum drywall. At the top of the walls, the design called for a built-up soffit to hide the large HVAC ducts that run around the perimeter of the room (*Figure 6*). The intent was to have the polyethylene sheeting taped to the FSK backing on the roof insulation, another almost impossible task.

During the installation, the laps in the polyethylene wall sheeting were not taped or sealed (*Figure 9*), nor was the polyethylene sealed to the foil-faced insulation at the ceiling level. In fact, the polyethylene vapor barrier was held back 1½ in (the thickness of the 2-in x 4-in furring strips), leaving ample opportunity for an airflow shortcut to exist in the vapor barrier, exposing the uncovered portion of the CMU exterior walls and permitting direct air access to the adjoining large attic areas through openings in the taped FSK and directly through the uncoated CMU walls. It needs to be noted that plain CMU is by no means a vapor barrier or an air barrier.

No particular design or construction attention was given to the small office and storage space adjacent to and part of the pool space.

DISCOVERY AND INVESTIGATION

A few weeks prior to occupancy, the pool was filled with water and a punch-list walkthrough with the architect's representative was scheduled in late January. During the course of this walkthrough, a number of small water stains were noted on the beveled cedar ceiling boards on the ceiling with a note on the punch list to repair noted "roof leaks." Within a few days, it became apparent to the owner's representative that there were no roof leaks but, rather, significant condensation problems in the roof assembly.

The ensuing investigation included making small inspection openings in the roof system by removing shingles and some plywood sheathing, removing portions of the cedar ceiling and gypsum soffits for a view inside the wall and interior soffit assemblies, and a review of the attic spaces above the adjacent locker rooms between the pool room and adjacent facility.

The investigation quickly found the following:

- There was a large disconnect around the entire perimeter of the interface between the ceiling and the walls where the polyethylene vapor barrier stopped at the 2-in x 4-in furring strips. The air/vapor barrier was by no means continuous (*Figure 8*).
- On the walls, a 6-mil polyethylene vapor barrier was behind the gypsum wall board; however, the polyethylene sheets were lapped but not sealed or taped (*Figure 9*).
- Penetrations in the polyethylene vapor barrier around outlets, piping conduits, and lighting fixtures were not treated with any particular attention to detailing or sealing.
- A massive amount of airflow and condensation was occurring in the compact roof assembly above the pool room.
- A massive amount of air flow and condensation was occurring in the attic between the pool room and the adjacent portions of the building.

Figure 10 – Icicle formations where condensation was dripping from the pool-room eave.

- Condensation was dripping from the eaves and forming icicles at night along the perimeter of the building (*Figure 10*).
- Large-scale wetting, warping, delamination, and buckling of the plywood roof panels above the pool room and adjacent attic space were observed.
- Widespread mold infestation in the locker room attics was noticeable in the portion of the adjacent attic areas close to the pool room (*Figures 11* and *12*).
- Condensation in the locker room attic was occurring on the underside of the roof sheathing and freezing (*Figure 13*).
- The foil-faced FSK "vapor barrier" facing on the fiberglass bats at the ceiling space had all the joints taped with metal tape, and the batts were taped to the heavy timber trusses and the CMU walls at the exterior perimeter (not practical). However, it was apparent that there were many opportunities for air transfer through small openings in the FSK taped edges (*Figure 14*).
- Moisture at the roof ridge vent was condensing to liquid water, then into ice along the length of the ridge. On a 25°F January morning, the air measured at the ridge of the roof was 68°F and 97% relative humidity (*Figure 15*).
- The design had called for the installation of two attic access hatches in the ceilings of the pool equipment room and aquatics office. These hatches were allowing rapid air infiltration from the pool space directly into the adjacent nonpool room attic spaces.
- Saturated fiberglass roof insulation above the pool room ceiling was observed.
- The HVAC system appeared to be working properly and was not contributing to the problems.

As one might expect, the architect defended the design and pointed at the contractor for poor workmanship, and the contractor pointed at the architect for defective design and construction administration ser-

Figure 12 – Biological growth and buckled sheathing at the attic space above the aquatics office.

Figure 11 – Biological growth on sheathing in attic space above equipment room prior to occupancy.

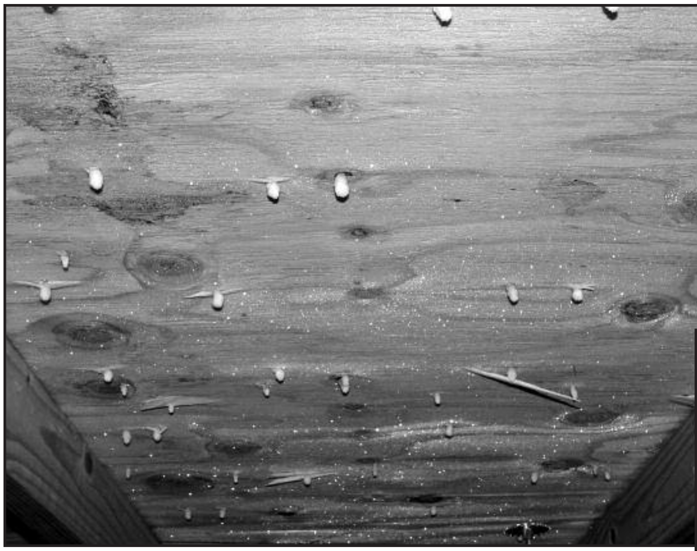


Figure 13 – View of condensation ice formation on the underside of the locker room attic roof sheathing.

Figure 14 – View of condensation dripping from behind the FSK facing. It is not practical to tape FSK to CMU.

vices. The owner filed a claim against both. The contractor quickly stepped up to work on a solution to correct the problems. The architect took longer but eventually did the same. In the meantime, the owner hired a third-party consultant to review the findings and make a recommendation for the required costly repairs.

Although there were significant issues with the wall assemblies and the installation of the polyethylene vapor barrier, the project team focused on the roof assembly and the massive amount of air leakage that was occurring from inside the pool room into the roof structure and adjacent attic spaces. The owner hired an industrial hygienist to test the inside of the building for mold. Following a determination that there was no interior impact on the building, the building opened with the comforting knowledge that warmer weather was coming and the condensation issues would cease for the spring and summer seasons, allowing the team the time to evaluate repair options and plan for the repairs prior to the onset of cold weather again the following fall.

After evaluating both the wall and roof assemblies, the project team elected to leave the wall assemblies as is, given that no visibly detrimental effects from the deficiencies in the placement of the vapor barrier had become evident, and an analysis demonstrated that there was enough hygroscopic absorption, outward drying, and cavity ventilation in the durable masonry wall assembly to accommodate the vapor and air transmission that might occur during the mild winter months. If this project were in a colder climate, the decision would have been different.

Figure 15 – View of condensation dripping from roof ridge vent.

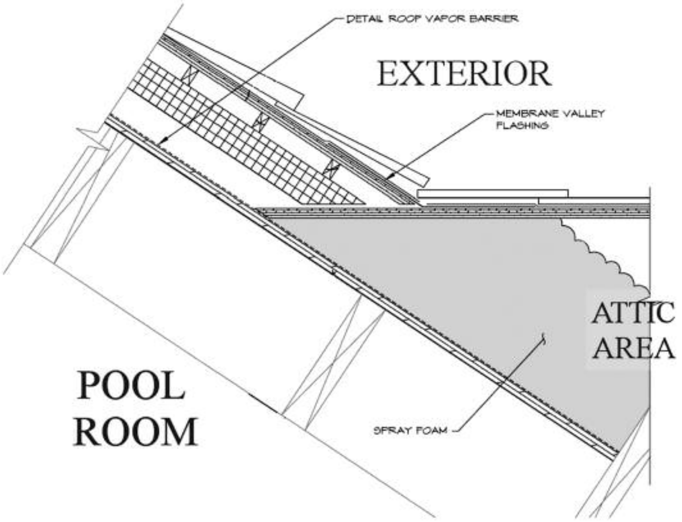


Figure 16 – Repair detail of the intersection of the new pool roof assembly and the adjacent attic area where SPF was installed to create an air/vapor seal.

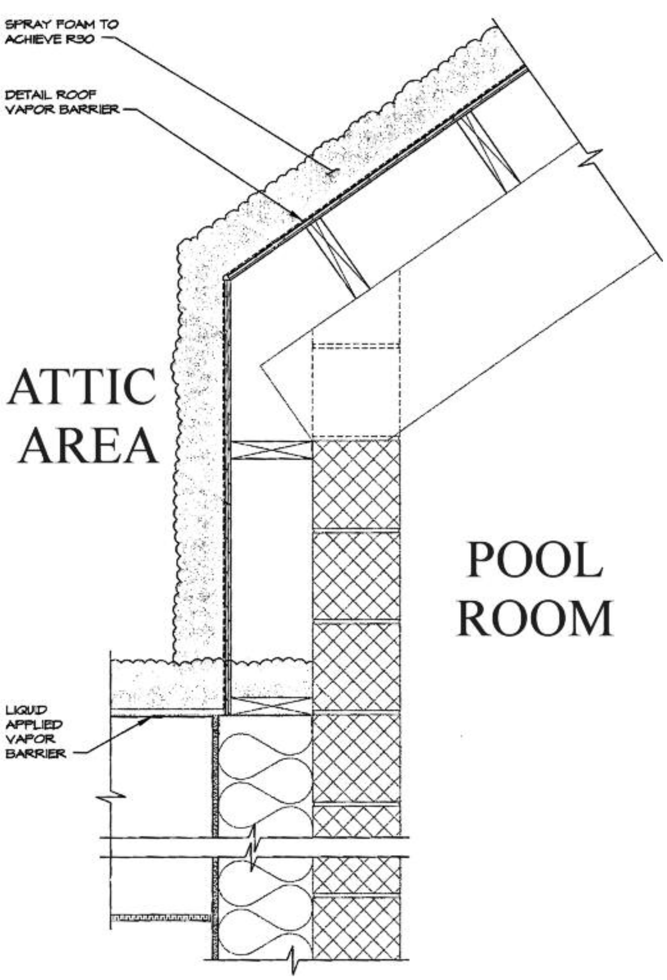


Figure 17 – Repair detail where SPF was used to create an air seal between the locker room attic and adjacent pool room and pool equipment storage room.

REPAIR OPTIONS

Two preferred options emerged as possible solutions for repairing the roof assembly. There was a desire to demolish a minimal part of the building as practical and to affect the community population as little as possible. These included an inside repair option and an outside repair option.

1. The inside option involved removing all of the beveled cedar ceilings, the 2-in x 4-in furring strips, and the FSK-faced fiberglass insulation; treating and removing any mold that might have accumulated in the compact roof structure; and replacing plywood roof sheathing panels as necessary. The remaining exposed cavities could be filled with spray polyurethane foam (SPF), creating an air/vapor barrier and also serving as the insulation to keep the structure below the dew point. Then new cedar panels could be reinstalled. This approach required a messy interior repair, scaffolding the entire pool space, and likely replacing the expensive cedar ceiling, as it was not going to come off cleanly.
2. The outdoor option involved removing the roof shingles, sheathing, all of the insulation, and the FSK facing from the top side; installing new sheathing to fully support a 40-mil, self-adhered air/vapor barrier membrane, 4 in of polyisocyanurate rigid-foam insulation placed in two layers, another layer of sheathing on vent strips, an underlayment, and new roofing shingles. This option allowed for a cleaner repair with minimal interior disturbance but also exposed the building to weather events (*Figures 16* and *17*).

Both options required removing all of the damaged and most of the moldy roof sheathing on the adjacent attic roof over the locker rooms and offices, as well as air sealing and better insulating the common wall and sloped roof between the pool room and adjacent attic spaces and applying a vapor barrier coating on the walls and ceilings of the office and storage room to tie those spaces to the adjacent pool room and separate those gypsum wall assemblies from the rest of the building.

Option 2—the outdoor option—was selected, and detailed repair documents were prepared by the third-party consultant.

THE REPAIR

The work was timed to allow three summer months to make the repairs prior to the onset of colder fall weather. Nearly all the major work was performed from the outside of the building, and the beveled cedar ceiling did not have to be removed. This approach required only a partial building shutdown during the repair work, provided a robust 40-mil self-adhered air/vapor barrier on the warm side of the insulation that

Figure 18 – View of SPF foam seal created at the building perimeter at the intersection of the top of the masonry wall and the roof eave. New sheathing supports 40-mil vapor barrier plus a ventilated roof assembly (not installed). Perimeter sheathing is set in wet foam and nailed to promote an airtight seal.

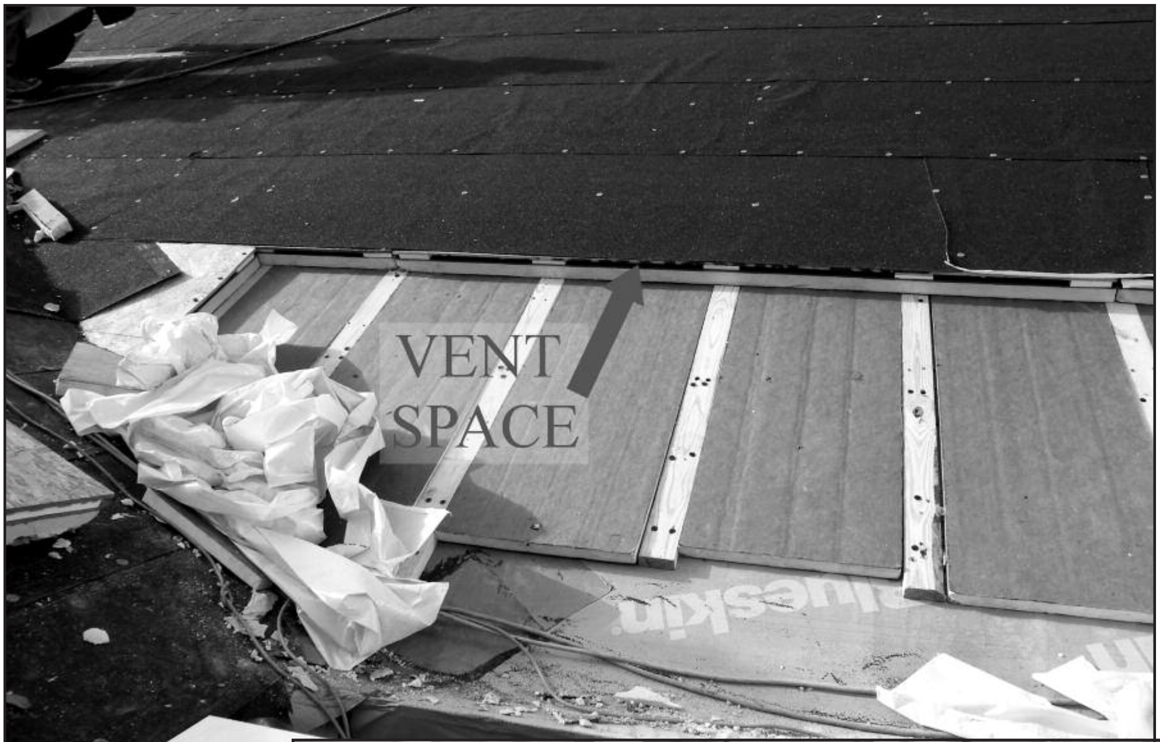


Figure 19 – View of the new 40-mil air/vapor barrier (blue), plus two layers of staggered polyisocyanurate rigid insulation, plus venting spacers, roof sheathing, and shingle underlayment.

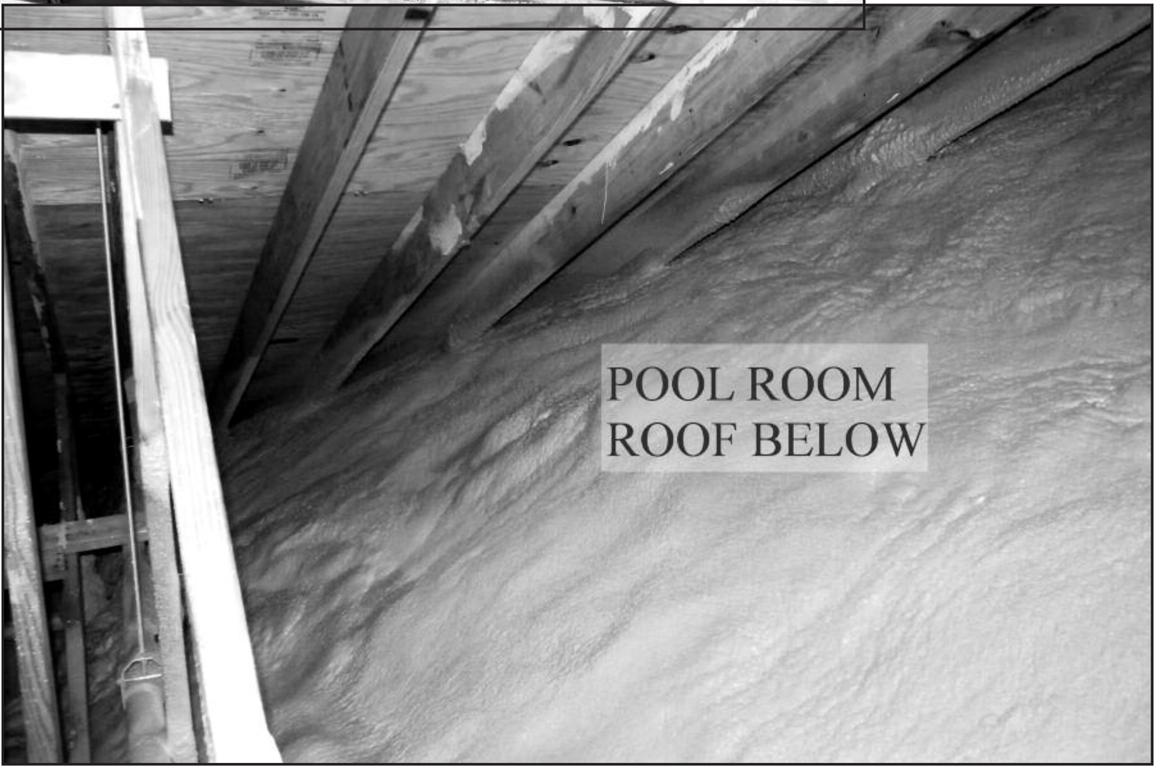


Figure 20 – View of SPF insulation installed in the adjacent attic creating an air/vapor barrier between the attic and pool-roof assembly prior to the application of an ignition barrier.

was fully supported by the new roof decking.

In addition, SPF was used to create an airtight plug around the entire perimeter of the eave and to tie the roof system to the wall system (*Figure 18*). SPF was also used to create an air- and vaportight seal around the adjacent connecting attic and the pool room roof structure (*Figures 17* and *20*). The aquatics office and equipment storage room, which were part of the pool area, were treated with a liquid-applied air/vapor barrier by applying an impermeable air block on the walls and ceilings. Both of the attic access hatches were moved to other parts of the building, ensuring an air-tight assembly between those spaces and the adjacent nonpool building areas.

LESSONS LEARNED

Ultimately, the owner got a building that will perform long term. The lessons learned were costly for the design and construction team members and, unfortunately, are lessons that are repeated often in the industry. If there was a silver lining in this for the owner, it was that the failure occurred early, before the project was closed out, thereby giving the owner the benefit of being in the superior financial position whereby he held substantial retainage and was able to keep the attention of the rest of the project team. Lessons learned included the following:

- Demanding that building types require durable air/vapor barriers where the plans and specifications are fully developed, with critical conditions clearly illustrated. In this case, even if the specified vapor barrier were installed in the roof assembly, it is likely that building failure would have occurred in a few years rather than a few weeks. The original design simply was not a durable solution, given the conditions and the skill of the construction team. There are durable polyethylene sheet options where heavy, 10-mil or thicker scrim-reinforced sheeting is installed with a number of specialty accessories to ensure an airtight installation. These systems often require double-sided butyl tape on every stud and every seam to ensure through-fastener sealing. Airtight electrical box enclosures are provided that are sealed to the poly sheet. This approach could have worked if the team had started with such a design, and it is worthy of consideration.

- Always take a very serious look at any substitution requests, and see how the proposed changes affect the entire design.
- Unintended air movement can carry moisture far in excess of moisture transmission via diffusion through building materials. The assemblies must be air- and vaportight, continuous, durable, and able to be economically installed.
- Depending on building size and budget, consider and specify independent testing of various building assemblies and/or the entire building enclosure for airtightness, using whole-building fan testing techniques. Look for air leakage rates of less than 0.1 cfm/sf of enclosure surface area for whole-building tests.
- Experienced staff (not just firms) must bring their oversight to the design and construction of critical air/vapor barrier components. This may also require a third party to review the design and become part of the construction quality-assurance efforts.
- Perform a dew point analysis for all enclosure assemblies, and ensure that condensation potential is eliminated.
- Review substitution requests with extreme caution.
- Conduct preconstruction meeting(s) with all the pertinent trades, review the design intent, and have qualified persons inspect the work frequently.

This case study emphasizes the need to build airtight enclosures. This lesson is not only for pool structures but also applies to almost all conditioned buildings where the control of air (and therefore moisture) movement is critical to long-term building performance, energy efficiency, and indoor air quality.