Air Barriers in High Interior RH Specialty Buildings: Considerations for Control of Moisture-Laden Air in Museums, Labs, and Natatoriums

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ABSTRACT

Air barriers in building enclosures are still not widely mandated by building codes in the United States. However, acceptance of incorporating air barriers into new building enclosures is growing within the building design and construction industries, and attempts are being made to add them to existing buildings.

Care must be taken when examining the placement of and requirements for air barriers with specialty buildings such as museums, certain labs, and natatoriums, which can maintain interior relative humidity levels ranging from 35 to 65% when properly controlled and well above 65% when inadequately controlled.

This paper will use examples from projects on which our firm has worked to discuss a method to determine air barrier requirements, including secondary interior air barrier elements. We will discuss considerations for both new and existing construction of specialty buildings to control moisture-laden air. In addition, we will briefly review some of the macro and micro climate considerations for examining moisture-laden air flow with specialty buildings.

INTRODUCTION

Air barrier use in North America can be traced back to the 1970s during the energy crisis, when designers realized the benefits of controlling air leakage and the potential savings in associated heating and cooling costs. Mandatory air barriers became part of the National Building Code of Canada in 1986, but they have not yet become a national code requirement in the United States (although Massachusetts, Wisconsin, and Michigan currently require them in their energy codes). High humidity buildings can benefit most from continuous air barriers because they are highly susceptible to accelerated deterioration from uncontrolled migration of moisture-leaden air. Guidelines for whole-building airtightness and air barrier system design, however, are not readily available to designers. The design concept as a whole is still in its infancy.

The need for a properly designed air barrier system becomes more critical as the moisture loads within the building increase. Specialty buildings require careful design, implementation of the construction, and oversight of the air barrier system. All specialty buildings require an in-depth understanding of heat, air and moisture movement and control as well as a clear understanding of the interaction between the mechanical systems and the building enclosure. Failure to properly implement an air barrier system in high humidity buildings can result in a variety of problems, ranging from effloresence and ice formation on cladding materials to corrosion and structural failure of susceptible components.

Consideration must be given to:

- the climate in which the building is located;
- the effectiveness of the mechanical systems at moving air and controlling moisture; and
- the communication between the high humidity zones and other portions of the building with different intended temperature and /or relative humidity (RH) requirements, such as offices or classrooms

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DRIVING FORCES

The driving force behind air leakage is a difference in air pressure across building assemblies. Air naturally flows from regions of higher air pressure to regions of lower air pressure. While controlling building air pressure is an obvious method of controlling air leakage, the ability to control building pressure is affected by the airtightness of the building enclosure. If the magnitude of air leakage through the building enclosure exceeds the airflow capacity of the mechanical system, that system will not be able to effectively control the pressure within the building. Even if the mechanical system has sufficient capacity to overcome air leakage and maintain the required air pressure differential, the cost of heating, cooling, and dehumidifying leakage air can be substantial. For this reason, coordination between the building enclosure engineer and the mechanical engineer is critical when designing or retrofitting air barrier systems.

In addition to mechanical pressurization, two other factors can affect airflow through the building enclosure. The first factor is wind. Wind flowing around a building will create an effective positive pressure on the exterior of the windward side and an effective negative pressure on the leeward side. The second factor is stack pressure. The natural tendency of warm air to rise can, in tall enough buildings, create a negative pressure at the base of the building and a positive pressure at the top of the building. In buildings with no, or a poorly constructed, air barrier, the combined effects of wind and stack pressures can exceed the capacity of the mechanical system and govern the pressure differential across the building enclosure.

MOISTURE LOADS AND CONTROLS

In order to design an appropriate air barrier system in any given building, an understanding of the relevant moisture loads is essential. Moisture loads in buildings can be categorized into three major groups:

1. *Bulk water.* Bulk water loads include precipitation as well as loads related to any element holding water (pools, fountains, etc.). The control of these loads through the use of water management systems and waterproofing systems will not be discussed in great detail in this paper.
2. *Air movement, specifically the movement of moisture-laden air.* Differences in air pressure may exist between the exterior and the interior or between two separate spaces/rooms/floors within a building. Air barrier systems are used to control the resulting air movement and are the main focus of this paper. The amount of moisture present in the air in humidified building environments can be as much as two to three times that of a typical office or residence. These increased moisture levels greatly increase the incidence of condensation and other moisture problems, with some problems developing only months (as opposed to years) after such a building is occupied.
3. *Moisture movement due to diffusive vapor transfer.* Moisture movement due to diffusive vapor transfer occurs due to a difference in water vapor pressures between elements. This can occur due to differences of moisture content between the exterior and the interior air or differences between interior spaces. This can also occur due to differences in moisture levels within a single element or between adjacent elements. The changes in interstitial moisture levels can occur due to wetting and subsequent drying events as well as air leakage across the building enclosure. Vapor diffusion is controlled by means of a vapor retarder. While a discussion of vapor retarders is beyond the scope of this paper, they will be mentioned insofar as they affect the placement of the air barrier within the building enclosure.

DETERMINING AIR BARRIER REQUIREMENTS FOR SPECIALTY BUILDINGS

Climate Considerations

The hygrothermal performance of enclosures in specialty buildings can be sensitive to even modest changes in climatic conditions. Climatic data specific to the site or exact location of the specialty building need to be used in the analysis and design of enclosures in specialty buildings. Regional climate considerations may not be specific enough to determine climate idiosyncrasies at the building site; instead, locally-recorded data (either at the site itself or at a reasonably close weather station) is necessary.

Just as important as the exterior climate are the interior environmental parameters; these may be parameters for the entire building or for individual rooms or spaces within the building. In some buildings, such as those containing labs or archive facilities, individual rooms or spaces can have temperature, relative humidity, and air pressure requirements that are significantly different than those in the rest of the building.

The level of control that the air barrier system needs to provide is dependent on the use of the building and the accompanying range of humidity and temperature the building is designed to maintain.

Water Vapor Migration

Although the magnitude of moisture transport via airflow is much greater (as much as 50 to 100 times) than that by water vapor migration, the two phenomena must be considered together when designing the air barrier. Due to the relatively low driving force behind vapor diffusion, vapor retarders can contain small gaps or unsealed seams and still provide adequate performance. This is one of the primary differences between air barriers and vapor retarders – those same defects would significantly reduce the performance of an air barrier. However, designers must keep in mind that although vapor retarders typically do not function as air barriers, many air barrier materials do function as vapor retarders.

In order to be effective, vapor retarders must prevent water vapor migration to low temperature areas of the building enclosure where that moisture can condense. Generally speaking, vapor retarders function best when installed on the interior side of the thermal envelope in cold climates and on the exterior side of the thermal envelope in warm, humid climates. Although interior vapor retarders are often penetrated by electrical fixtures and other wall components, these penetrations are typically small enough so as not to degrade the performance of the system. As discussed above, the same is not true for air barriers. In most buildings, the practical location for the air barrier is on the exterior side of the building sheathing, outboard of the primary structural frame of the building. In this location, continuity between roofs and walls and across floor levels is easier to achieve, and the direct access to the system during installation makes sealing of penetrations relatively straightforward.

Problems may develop if the location of the vapor retarder is not coordinated with the location of the air barrier. A vapor impermeable air barrier installed outboard of the insulation in a cold climate will become a vapor retarder on the "wrong" side of the thermal envelope. Even in the absence of water vapor diffusion, airflows within the building caused by stack effect or mechanical system operation may allow moisture-laden interior air to flow across the interior side of the air barrier, causing condensation on the cold surface. These issues can be addressed through the use of continuous rigid insulation on the outboard side of the barrier, which keeps the temperature of the barrier high enough to avoid condensation (due to either direct airflow or water vapor diffusion). In this case, the insulation needs to be in intimate contact with the air barrier to mitigate the flow of exterior air between the air barrier and the insulation. The opposite is true in warm, humid climates, although in some cases condensation on the air barrier is acceptable if the air barrier is located within an exterior drainage cavity and functions as the water barrier as well. While in theory the use of both interior and exterior vapor retarders would prevent moisture migration in both directions through the enclosure, retarders would also create a "vapor trap" that prevents built-in construction moisture or moisture from incidental leakage from drying out.

Computerized hygrothermal analysis tools can be used to determine the optimal vapor permeance for air barriers, based on their placement within a wall system and the properties of other components within the walls. The effects of wetting and drying (including the drying of construction moisture) can be evaluated, allowing designers to create wall systems that can tolerate some degree of moisture. In some cases, insulation can be installed on both the interior and exterior side of a vapor-impermeable air barrier, creating wall systems with higher thermal insulation values. These systems must be carefully analyzed, since the right balance of insulation (on the interior vs. exterior side of the barrier) will vary with climate type.

AIR BARRIER SYSTEMS

Various types of materials can be used as air barrier materials, including, but not limited to, liquid-applied membranes, sheet products, some expanding foam insulations, some roofing membranes, concrete walls, and sheathing boards. The joining of these materials and the assemblies they are part of is completed typically by transition elements (air barrier components) to form the air barrier system. Skylights, doors and windows will also become integral parts of the air barrier system.

Liquid-Applied (Field-Cured) Membranes

Liquid-applied membranes are either sprayed, rolled or trowel-applied onto a rigid substrate. They typically require sheet product transitions at flashings, penetrations, and transitions between other elements and assemblies of the air barrier system. They also require more field quality control than sheet products to ensure proper and consistent application rates to achieve the thickness necessary for the material to function as an air barrier. Joints between sheathing layers, concrete walls, and similar transitions where movement may occur require, at a minimum, joint reinforcement to prevent cracking the membrane. Supplemental mechanical attachment and/or reinforcement with sheet membrane at these joints provides a durable detail. Spray application requires special precautions on all sites, but especially on structures that can experience high wind loads that increase the risk of overspray onto adjacent surfaces. Products are available in low vapor permeance (5.72E-11 kg/(Pa*s*m^2) [1 imperial perm] or lower), mid vapor permeance (5.72E-11 kg/(Pa*s*m^2) to 5.72E-10 kg/(Pa*s*m^2) [1 to 10 imperial perms]) and high vapor permeance (greater than 5.72E-10 kg/(Pa*s*m^2) [10 imperial perms]).

Sheet Products

Since they are not continuously bonded to a substrate, mechanically-fastened sheet products may lack sufficient strength to resist negative wind pressures without pulling away from the fasteners or otherwise being damaged. These products function best when "sandwiched" between materials that provide rigidity. Although typically vapor-impermeable, self-adhering sheet products are now becoming available in vapor permeable versions. Sheet products with thick facers generally have a memory: they do not follow geometric change with complicated architecture very well and tend to "flatten out" and pull away from substrates at interior corners and sharp bends. For this reason, additional mechanical attachment is often necessary. Zones of supplemental mechanical attachment can be "stripped in" with additional membrane. Alternatively, sharp corners and the like can be detailed with another membrane that does not have a memory, such as uncured EPDM, provided it is compatible with the main air barrier membrane. Most self-adhered membranes have the ability to form a seal around small fasteners (typically screws and some types of nails), but larger or irregularly-shaped penetrations will require an additional seal.

Expanding Foam Insulations

In addition to providing efficient thermal insulation, expanding foam insulations can perform as an air barrier material that becomes part of the air barrier system. They typically require transition air barrier components, like sheet goods, at transitions and penetrations. Spray foam insulations have the added unique advantage of being able to fill irregularly-shaped cavities, providing an air seal where most other products are unsuitable.

As is the case with spray-applied membranes, application requires special precautions when spraying on high rise and in high wind applications. Some foams have low vapor permeance (5.72E-11 kg/(Pa*s*m^2) [1 imperial perm] (1 imperial perm or less) while others have higher vapor permeance. Some foams use a water blowing agent, which must be allowed to dry out to prevent it from becoming trapped within the enclosure. Embedment of sheet products and other transition elements requires compatible materials and sufficient overlap into the foam. Bonding of the foam to the product is also necessary to ensure that under contraction and expansion of the structure, the localized element does not fail by tearing out the foam or pulling the foam away from the surrounding substrates. When selecting foam insulations for air barrier applications, consideration must also be given to the exposure of the foam (UV radiation, rainwater, etc.), as not all expanding foams are designed to be weather-resistant.

Sheathing Products and Concrete Walls

Most sheathing board products, concrete walls, and precast concrete panels have sufficiently low air permeance to function as air barrier materials. However, the joints between boards or panels and the fasteners penetrations in some board products need to sealed. This is typically done on board products using liquid applied or sheet membranes. The sealant joints between concrete walls or precast panels also perform as air seals when the concrete is the intended air barrier system for the wall assembly As is the case with all air barrier assemblies, joints and penetrations through these components will undermine the air barrier if not sealed properly.

Doors and Fenestration

When designing doors and fenestration (such as windows and curtain walls) one must consider both the airtightness of the component as well as the integration of that component with the surrounding air barrier. A high-performance window will provide little benefit if it is not properly integrated with the air barrier on the surrounding walls. Likewise, a perfectly integrated window with poor weather stripping and a high air leakage rate will reduce the overall performance of the air barrier. Since air will naturally flow through the path of least resistance, the concept of an air barrier being a system of interconnected materials, assemblies and components is especially true at doors and fenestration - the system is only as strong as its weakest link.

CONTINUITY BETWEEN AIR BARRIER ELEMENTS

Continuity between air barrier materials, components, and entire assemblies is essential to its proper performance, especially with specialty buildings, where minor voids and discontinuities in the system can lead to significant moisture problems. As noted by Lemieux and Totten (NIBS 2005), continuity should be shown on drawings on building sections, and plans and should be traced out on the drawings in order to identify all interfaces and conditions that will require details to provide guidance on design intent for continuity. A separate set of details can be added to the drawings to indicate the requirements for the air barrier. Transitions are best illustrated using both 2-dimensional and isometric details. For complex assemblies, a series of details shown in sequence can provide clear direction (NIBS 2005). The following list of details, at a minimum, should be developed (NIBS 2005):

1. At the interface between different wall types or claddings
2. At expansion joint locations
3. At penetrations (roof, below grade or wall)
4. At louver locations
5. At door and fenestration (window, curtainwall, skylight, etc.) openings
6. At the roof-to-wall transition for each type roof or wall type on the project
7. At the floor-to-wall intersection
8. At the wall-to-below-grade transition
9. At inside and outside corners
10. At joints and fastener penetrations where sheathing boards or rigid insulations are the intended air barrier.
11. Roof membrane joints
12. At sun-shade framing or other similar framing penetrations
13. At all other unique, project-specific conditions requiring additional information to complete the air barrier system installation

INTERIOR AIR BARRIERS

An often overlooked component of the building air barrier system is that which separates interior high humidity zones from adjacent, non-humidified or even non-conditioned interior zones. This is more of a problem in natatoriums, which are commonly constructed as part of a larger complex of buildings, but may also occur in museums (at non-humidified storage spaces or offices) or laboratory spaces (where adjoining rooms may have different conditions).

Since spaces like offices, storage rooms and attics are not typically designed to function under high humidity conditions, moisture-laden airflow into those spaces through unsealed interior partitions may lead to significant damage to interior components. In addition, leakage into adjacent spaces may cause damage to exterior components as well, if those spaces are located near exterior walls which are not designed to tolerate high humidity. Unless a space is specifically designed to tolerate high humidity, it must be completely sealed off from any adjacent spaces that may act as moisture sources.

It is tempting to rely on standard wall components such as gypsum wallboard to provide interior air barriers. Although materials such as building boards may be inherently airtight, joints, connections, and penetrations (including plumbing and electrical fixtures) will reduce their effectiveness at controlling airflow. Materials such as sealants and membranes are typically necessary to seal around penetrations and provide airtight construction. The use of these materials is complicated by two factors. First, durable air barrier materials are typically designed for exterior use and may contain volatile organic compounds (VOCs) or other substances that make them difficult to use in interior spaces. Second, interior air barriers must often be installed in highly visible locations. This requires additional care to conceal materials and reduce the aesthetic impact of the air barrier seals. Coordination with architects and interior designers is critical in these applications, since minimizing aesthetic impact may be necessary to "sell" the air barrier system.

AIRFLOW-RELATED PROBLEMS

There are several problems associated with air leakage (both infiltration and exfiltration) in high humidity buildings. These are discussed below.

- **Condensation:** The primary problem with air exfiltration is condensation within the building enclosure. Warm, humid air flowing through building enclosures in cold and even some mild climates will produce condensation on surfaces that are colder than the ambient dew point temperature. The magnitude of condensation in high humidity buildings is much greater than in non-humidified buildings since the high interior dew points will cause problems for a much greater portion of the year. Condensation can cause problems ranging from obvious efflorescence on exterior masonry to hidden corrosion or microbial growth within the enclosure. Hidden problems can be much more damaging to the enclosure, as they may go unnoticed for months or even years before being discovered by the building occupants.
- **Heat Loss/Gain:** Air that leaks through the building enclosure can either add or remove heat from building zones, depending on the direction of the flow. This can produce problems ranging from increased heating and cooling costs to reduced interior environmental control if the added heat loads exceed the capacity of the building mechanical system.
- **Humidity Control:** In humidified buildings, air leakage through the enclosure can also affect the interior humidity control. During the winter, air exfiltration will remove moisture from the interior environment that will need to be replaced by the humidification system. Infiltration of cold, dry air can also "dilute" the interior air and lower RH levels, adding to the humidification load. Likewise, during the summer, air infiltration will add moisture to the interior air that must be removed by the mechanical system. Depending on the magnitude of the leakage and the capacities of the mechanical equipment, the equipment may not be able to keep up with these additional loads.
- **Contaminant Control:** Although not an issue for the mechanical system, airborne contaminants that enter the building through gaps in the enclosure can be an issue for the contents of the building (especially in the case of museums and archives, which house and display fragile – and often priceless– artifacts). In laboratory spaces, isolation and containment are often necessary for maintaining "clean room" environments or containing dangerous substances. In these cases, airtight interior partitions are critical.
- **Air Pressure Control:** Similar to contaminant control, spaces such as laboratories, clean rooms, and quarantine spaces/operating rooms in hospitals rely on positive or negative air pressure to isolate them from surrounding areas. If air barriers in these types of spaces are not properly designed and constructed, problems can range from an increase in the operating cost of the spaces to a lack of containment/isolation if the required pressures cannot be maintained. The consequences of containment loss can be severe, especially in areas which must either contain dangerous substances or protect occupants from such substances in the surrounding environment (i.e., isolation rooms for immune-compromised patients in hospitals).

CASE STUDIES

The following case studies are from projects that the authors' firm has worked on over the past three years. These case studies illustrate many of the points discussed above, including the investigation and repair of ineffective or non-existent air barrier systems.

CASE STUDY #1—A COLD CLIMATE NATATORIUM

The authors' firm was asked to investigate the cause of interior and exterior damage to an institutional natatorium in the Northeast U.S. that developed soon after construction.

The natatorium was constructed as part of a larger athletic complex, housing weight training facilities, squash courts, an ice rink, and office and storage spaces. The enclosures around these spaces were all of similar construction, using single-wythe brick veneer cavity walls installed over structural steel framing, with concrete masonry infill (backup) walls. Extruded polystyrene insulation, 51 mm (2 in.) thick, was installed in the brick cavity over a layer of asphaltic damp proofing on the backup concrete masonry unit (CMU) walls. A standing seam aluminum roof was installed over perforated acoustical metal decking, with approximately 203 mm (8 in.) of glass fiber batt insulation between the decking and the roof panels. A large skylight was installed at the ridge, roughly centered over the pool. A stairwell/bell tower, rising approximately 1.5 m (5 ft) above the roof ridge, was connected to one end of the natatorium. The bell tower was part of the adjacent athletic building and was not intended to be humidified. Although eave vents were not installed, a continuous vent (interrupted only by the skylight) was installed at the roof ridge. No dedicated air barrier system was installed in the building, either in the exterior walls or between the natatorium and the adjacent zones.

During the first winter of the building's operation, the owner reported widespread efflorescence on the exterior brick masonry (Figure 1) and significant accumulation of icicles at the roof eaves (Figure 2). We investigated the building during the winter, when these problems were the most severe, and performed an infrared (IR) scan of the building to look for "hot spots," or areas of increased temperature on the exterior of the building that, when the building is positively pressurized, are indicative of warm air leaking from the interior of the building.

Figure 1 *Efflorescence on exterior brick masonry.*

Figure 2 *Heavy icicle formation at roof eaves.*

In addition, we measured the overall air leakage through the building enclosure using a dual-fan blower door assembly (Figure 3) performed in accordance with ASTM E779.

Mechanical System Operation

The natatorium space was conditioned by two large packaged air handlers that provided heating and cooling of the air, heating of the pool water, and dehumidification. The interior conditions in the natatorium were typically around 26.7°C (80°F) and 60% relative humidity (a dew point of approximately 18.3°C [65°F]).

Testing, Repairs, and Analysis

Our IR scan of the building indicated significant air leakage at the roof eaves, roof ridge, bell tower, and at the intersection of the natatorium with the adjacent athletic buildings. We confirmed these leakage paths using chemical tracer smoke. During our initial blower door test, we used two fans, each with a capacity of approximately 2360 L/s (5000 ft^3/min), to depressurize the interior space. However, even with both fans running at full capacity, we were unable to generate a measurable air pressure differential between the interior and the exterior. While our testing did not provide quantitative data regarding the airtightness of the enclosure, it did show that the overall air leakage through the building enclosure exceeded 4,720 L/s (10,000 ft^3/min) (for reference, the design ventilation requirement for the natatorium was 4340 L/s [9,200 ft^3/

Figure 3 *Dual-fan blower door used to test whole-building air leakage rate.*

min]). The magnitude of air leakage through the enclosure indicated massive gaps in the building enclosure and the lack of a complete air barrier system.

We monitored the differential air pressure between the interior and exterior of the building using a digital differential pressure gauge in conjunction with electronic data loggers. We monitored the ambient interior and exterior temperatures during the same time. We took measurements at the lowest level of the pool (even with the pool deck surface). The results of this monitoring, performed during the month of December, showed that the pressure within the building was generally negative with respect to the exterior. Figure 4 shows that fluctuations in the differential pressure followed the same general trend as the exterior temperature, indicating that the pressure within the building was being dominated either by stack or wind pressure rather than mechanical pressurization.

We next calculated the magnitude of the stack pressure within the building over the course of our differential pressure monitoring. We plotted the differential pressure at the base of the building, the stack pressure within the space, and the sum of those pressures (Figure 5). This data showed that the magnitude of the stack pressure exceeded the pressure differential at the base of the building. The net pressure (i.e., the differential pressure near the top of the building) was positive, indicating a driving force for "pushing" humid air out of the building. This confirmed our findings that condensation due to humid air exfiltration through the roof was the cause of both icicle formation and efflorescence in the exterior brick veneer. The effects of stack pressure were particularly evident at the bell tower, which acted as a chimney drawing in humid air from the natatorium space, due to the lack of an air barrier between the two zones. Although not part of the natatorium space, some of the worst efflorescence in the building occurred at the bell tower due to the exfiltration of humid air from the natatorium (Figure 6).

Based on our investigation, we developed a scope of repairs to address air leakage through the building enclosure. As per the direction of the architect, we developed a phased repair plan for the building to install air barriers in critical locations. Phase 1 included removing the existing roof, installing an air barrier assembly integrated with the walls and surrounding buildings, and installing a new roof system to match (aesthetically) the existing roof system. Part of Phase 1 included installing air barriers at interior partition walls and wall-to-roof intersections. Since these locations were all visible from the interior, the air seals had to be concealed using painted ornamental sheet metal designed to "blend in" with adjacent components. Phase 2 included the addition of interior air barriers between the natatorium and adjacent zones, as well as removal of the exterior masonry to install an air barrier in the exterior walls at the roof eaves.

Following the Phase 1 repairs, we performed a second blower door test to measure the air leakage rate through the building enclosure. Prior to our testing, we reviewed the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) requirements for air pressure control in natatoriums. ASHRAE recommends that the air pressure within natatorium spaces be maintained approximately 12 to 37 Pa (0.048 to 0.149 in. of water) below the exterior (or adjacent interior) space. At a differential pressure of -12 Pa, we measured an overall airflow of approximately 3260 L/s (6900 ft^3/min) through the natatorium enclosure.

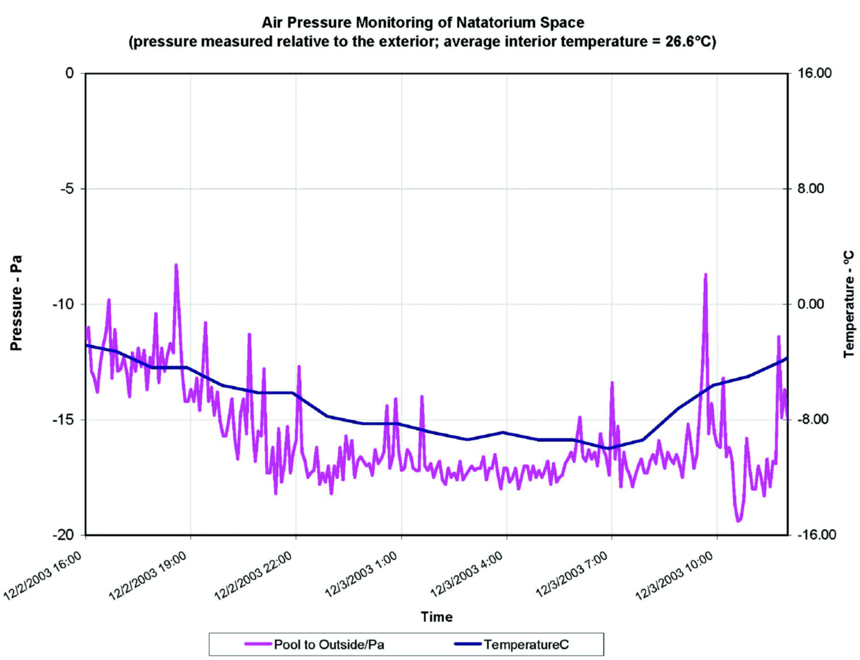

Figure 4 *Plot of interior air pressure (with respect to the exterior) and concurrent exterior temperatures.*

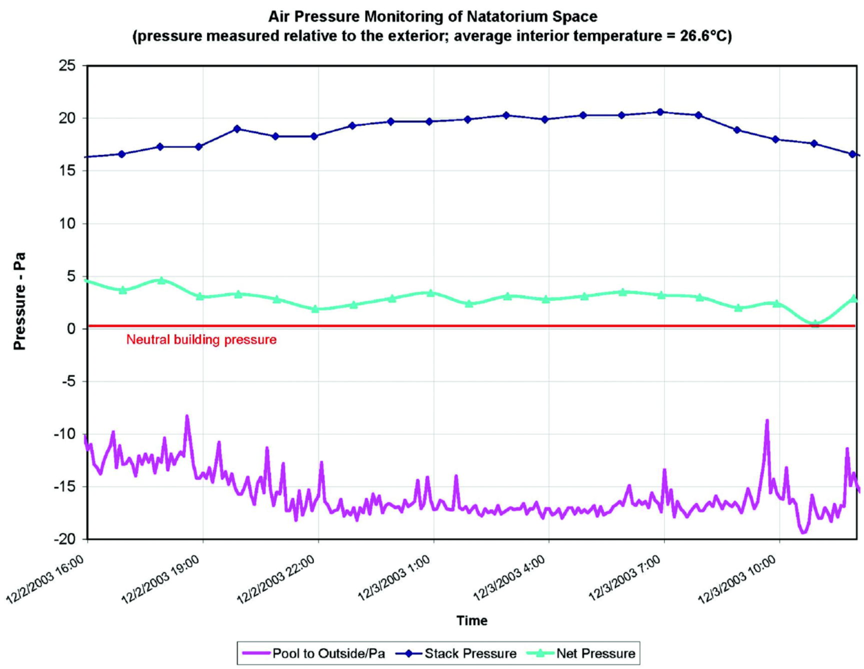

Figure 5 *Plot of interior air pressure (with respect to the exterior), magnitude of stack pressure within the space, and the net interior air pressure.*

Magnitude of Heat and Moisture Flows

Using the worst case scenario of 3260 L/s (6900 ft^3/min) of exfiltration occurring across the exterior building enclosure (as opposed to interior partition walls), we calculated the magnitude of both heat and moisture flow through the enclosure following the Phase 1 repairs. We used interior conditions of 26.7°C (80°F) and 60% RH and an exterior design temperature of -17.8°C (0°F, appropriate for the geographic location of the natatorium).

Heat Flow

The relationship between heat flow and airflow is as follows:

$$q_s = 0.001 * Q * p * c_p * dT$$

where

q_s = sensible heat flow (W)

0.001 = unit conversion factor

Q = airflow (m^3/s)

p = air density (approximately 1.168 kg/m^3 [0.073 lb/ft^3] at an interior temperature of 26.7°C [80°F])

c_p = specific heat of air (approximately 1 kJ/(kg*K) [0.24 btu/(lb*°F)])

dT = temperature differential (°C)

For this building and the parameters stated above, the approximate heat loss due to airflow at the design conditions is 171,400 W (585,000 btu/h). For comparison, we calculated

Figure 6 *Efflorescence on exterior of bell tower/stairwell. This area is outside (but adjacent to) the natatorium space.*

the conductive heat loss through the building enclosure under the same conditions:

$$q_s = U * A * dT$$

where:

U = overall heat transfer coefficient of the building (for this building, we calculated an approximate U-value for the enclosure of 0.5678 W/(m^2*K) [0.1 btu/h*sf*°F])

A = building enclosure area (m^2)

dT = temperature differential (°C)

For this building, the conductive heat loss through the enclosure at the design conditions is approximately 86,440 W (295,000 btu/h). Referring to the previous calculation, we found that the heat loss due to airflow is nearly twice the magnitude of the heat loss due to conduction alone.

Moisture Migration

The relationship between airflow and moisture migration can be expressed as follows:

$$q_m = 60 * Q * p * hr$$

where:

q_m = moisture flow (kg/hr)

60 = unit conversion factor

Q = airflow (m^3/s)

p = (approximately 1.168 kg/m^3 [0.073 lb/ft^3] at an interior temperature of 26.7°C [80°F])

hr = humidity ratio of interior air (kg moisture/kg dry air, approximately 0.0133 at 26.7°C [80°F] / 60% RH)

This equation assumes that all of the moisture in the air condenses to a liquid on some surface within the enclosure. As such, it represents the theoretical maximum amount of moisture that could be deposited within the enclosure at the design conditions. For this building and the parameters stated above, that amount is approximately 3.06 kg/hr (6.75 lb/hr) or 185 L/h (49 gal/hr).

These quantities represent the worst-case scenario of all exfiltration occurring across the exterior building enclosure. They do not take into account air leakage through the interior enclosure or conditions more severe than the design conditions. They are intended to provide a general idea of the severity of heat and moisture flow through the walls of a high humidity building.

The Phase II repairs were not implemented due to scheduling constraints and concerns regarding occupant disruption. Rather, based on the results of our second blower doors test, the exhaust capacity of the mechanical system was increased by upgrading the fans and drive systems. The repairs were successful because sealing the critical air leaks in Phase I was enough to enable the mechanical system to achieve and maintain a negative air pressure relative to the exterior. This is a good example of how coordination between mechanical engineers and building enclosure designers can produce successful results in buildings with imperfect air barriers.

CASE STUDY #2—A COLD CLIMATE MUSEUM

The authors' firm was asked to investigate the cause of staining on the exterior wood siding of a small museum in the Northeast U.S. that developed during the first winter of the building's operation.

Building Construction

The building was primarily steel-framed, with gypsum-sheathed exterior walls constructed with light-gauge steel framing. The primary roofs were sloped standing-seam lead coated copper, with a smaller single-ply EPDM roof between them. The sloped roofs tapered from a gable at one end to a flat edge at the other. The original building plans showed a self-adhered rubberized asphalt membrane installed over the entire building, including all walls and roofs. That layer was intended as a continuous air and vapor barrier. Extruded polystyrene insulation was installed outboard of the membrane in the walls, followed by vertical wood furring and painted cedar siding. The self-adhered membrane was returned into the window and door openings, and polyurethane foam insulation sealant was installed between the membrane and the window and door frames to provide continuity of the air barrier.

Prior to our initial site visit, we were informed that the self-adhered membrane in the roof had been replaced with 0.15 mm (6 mil) thick polyethylene sheeting as a cost-saving measure. With the exception of that change, the building was constructed in accordance with the project plans and specifications.

Mechanical System Operation

The mechanical system for the building consisted of multiple air handlers, each with humidity control and adjustable supply, return, and exhaust dampers (to provide air pressure control). The air handlers for the main gallery spaces below the sloped roofs were located in the attic space between the gallery ceiling and the roof deck. The attic space acted as a plenum, drawing air through the top of the stud-framed walls from below. This was possible since the insulation was installed on the exterior side of the air barrier, rather than between the studs. A continuous vent was installed at the base of the walls to allow conditioned air to flow into the attic and return to the air handler. All air handlers and other mechanical equipment (boilers, exhaust fans, etc.) were centrally controlled via a computer running proprietary software.

The mechanical system was designed to operate in two modes. In the first mode ("museum mode"), the system provided relatively constant conditions of 21.1°C (70°F) and 50% RH. In the second mode ("economy mode"), which had reportedly never been engaged, the temperature is controlled to approximately 21.1°C (70°F) but no humidity control is provided. In both operating modes, the system was designed to maintain a slight positive air pressure (with respect to the exterior) in the space. As previously discussed, this is often done in museums to prevent the infiltration of airborne contaminants into areas that store and display artwork.

Reported Problems

During the first winter of operation, the building occupants reported ice formation and staining on the exterior siding as well as accumulating water at the base of the "ventilated" stud-framed walls in the galleries. In response to these problems, the interior RH setpoint was reset to 40%. The lower setpoint reportedly resolved the issue of accumulating water on the interior but did not make any noticeable difference to the exterior ice formation and staining. The building owner was comfortable maintaining the lower RH level as long as it was kept constant. In addition, recognizing the cost savings of decreasing the interior RH from 50% to 40% (25% savings in humidification costs) emphasis was placed on addressing the exterior wall staining issues only.

Investigation

We performed our initial investigation in February 2005, after the interior RH was lowered to 40%. As part of our investigation, we performed an IR scan of the building to locate air leakage sites. The building mechanical system was operating normally (in "museum mode") during our scan. Figures 7 and 8 illustrate the typical temperature patterns that we observed during our scan. We found areas of elevated temperatures (lighter color) below the eaves of the sloped roofs as well as below many of the windows. The following morning (we performed our infrared scan during the night to maximize the temperature difference between the interior and the exterior, as well as avoid false readings due to solar exposure) we reviewed the exterior of the building in those areas.

We found widespread staining of the exterior siding, originating at the roof eaves and extending downward several feet (Figure 9). In some areas, we could see reddish-brown drip marks emanating from the lap joints between clapboards. At one set of strip windows, icicles had formed on the exterior clapboards, again emanating from the clapboard joints (Figure 10). We did not observe this phenomenon anywhere but below the windows and roof eaves. Upon closer inspection

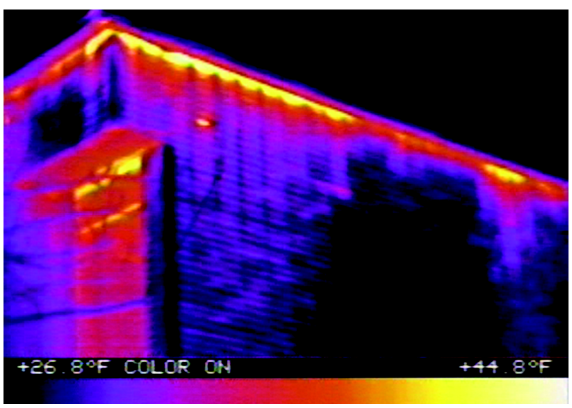

Figure 7 *Infrared scan of museum exterior. Lighter colors indicate higher temperatures at and below roof eaves.*

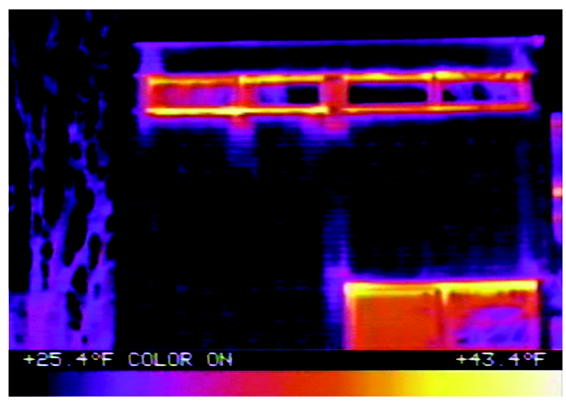

Figure 8 *Infrared scan of museum exterior. Lighter colors indicate higher temperatures around windows.*

Figure 9 *Dark staining on exterior clapboard siding of museum.*

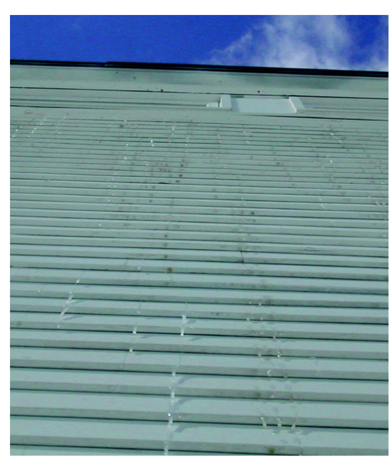

Figure 10 *Icicle formation below windows on exterior clapboard siding.*

of the clapboards, we observed large areas of peeling and blistering paint, often far from areas of staining.

Based on our initial IR scan, we made several sample openings in the exterior walls at the sloped roof eaves, as well as one opening in the field of the wall. Due to constraints related to occupant activities and schedules, we were not able to make any openings at or near the windows. Figure 11 shows the typical construction at the sloped roof eaves. The self-adhered membrane from the wall (blue membrane) does not extend onto the underside of the roof deck. The original building design included the same self-adhered membrane on the walls and below the roof; in that case, the air barrier would be continuous across the wall-to-roof joint. However, the membrane on the roof was replaced with polyethylene sheeting, which in turn was not connected to the membrane on the wall. The red arrow in Figure 11 indicates the primary air leakage path at the roof eaves. In some areas that we reviewed, the plastic sheet from the roof extended down past the membrane, although no attempt to seal this joint was apparent. In these areas, we found frost accumulation on the back side of the plastic.

Since we could not remove any of the windows, we reviewed the construction drawings for the windows below which we observed the heaviest staining and ice formation. The self-adhered membrane from the wall wraps into the rough window opening. A metal flashing pan is installed over the membrane, followed by wood windows. The joint between the window and the flashing pan was sealed with polyurethane foam insulation sealant, but no seal was installed between the metal flashing and the membrane. From the interior of the building, we observed that chemical tracer smoke applied at the window sill quickly becomes visible on the exterior of the building, confirming the flashing/membrane interface as a leakage path.

In the field of the wall, approximately 3 m (10 ft) below the roof eave, we removed several clapboards to examine the condition of the drainage space behind the siding. A thin layer of frost covered the back side of the clapboards as well as the sides of the vertical wood furring strips. The insulation and self-adhered membrane appeared continuous. We took several samples of the wood clapboards from this opening for further evaluation. We sealed each sample in a separate plastic bag to preserve the moisture content of the wood.

Analysis and Testing

We determined the moisture content of the clapboard samples that we took from the site in accordance with ASTM 1037. The moisture content (expressed as percent moisture by weight) of the samples was as high as 30%. For comparison, paint manufacturers typically recommend against painting cedar siding that has a moisture content higher than 15% due to the increased risk of paint failure.

We measured the overall air leakage rate through the building using a dual-fan blower door assembly. Prior to our testing, we closed all mechanical dampers and sealed all intake and exhaust ducts to ensure that we were measuring the air leakage rate through the building enclosure rather than the mechanical system. We measured an air leakage rate of 7.410 L/s/m^2 (0.325 ft^3/min/ft^2) of building surface area at a differential pressure of 75 Pa (0.3 in. of water).

Figure 11 *Primary air leakage path at roof eaves, where wall membrane terminates below the roof.*

Discussion

The high moisture content of the clapboards that we sampled indicated that they had been exposed to high moisture levels for an extended period of time. The primary air leakage path in the exterior enclosure was the roof-to-wall joint, where the air barrier on the wall was not sealed to the roof. Even if the plastic sheet on the roof was continuous and airtight, the joint between the membrane and the plastic would not be as reliable as a membrane-to-membrane joint. At interior conditions of 21.1°C (70°F) and 40% RH, condensation would occur on all surfaces below approximately 7.2°C (45°F). Given the location in the northeastern U.S., airflow into the exterior walls through the discontinuous air barrier would produce condensation in the wall system for a large portion of the year.

Air leaking through the roof-to-wall joint condensed on cold surfaces near the top of the wall, and the resulting condensation ran down the back of the clapboard siding. Air leakage from the window sills produced similar condensation. Although the cedar clapboards were back-primed, the constant exposure to water eventually led to a phenomenon known as “extractive bleeding.” Extractive bleeding occurs when water dissolves natural substances within the materials (tannins), creating a colored solution that stains the surface of the wood as it flows downward. We observed this process occurring in several areas of the building. Bleeding appeared to be concentrated near the eaves, where the heaviest condensation occurred, although moisture levels far from the air leaks still indicated wet conditions behind the clapboards.

Based on a survey of commercial buildings, Tamura and Shaw (1976) defined three air leakage classes for buildings. At a pressure differential of 75 Pa (0.3 in. of water), "tight" buildings are defined as having a leakage rate of approximately 2.28 L/s/m^2 (0.1 ft^3/min/ft^2), "average" buildings a rate of 6.84 L/s/m^2 (0.3 ft^3/min/ft^2), and "leaky" buildings a rate of 13.68 L/s/m^2 (0.6 ft^3/min/ft^2). Based on the leakage rate that we measured during out investigation 7.410 L/s/m^2 (0.325 ft^3/min/ft^2), this building would qualify as "average." While "average" airtightness may be adequate to prevent moisture problems in a non-humidified building, our findings at this building demonstrate that humidified buildings in cold climates require superior quality of construction in order to function effectively.

Remedial Repairs

Remedial work to the building was predicated on the condition that disruption to the building operation would be minimized. We developed a phased remedial repair plan to address the air leaks at the main roof eaves first, with the understanding that secondary air leaks around the building may become problematic once the primary leaks are "plugged."

Repairs at the eaves consisted of installing wood blocking to cover the gap between the top of the wall and the roof eaves, then covering that blocking with new self-adhered membrane (Figure 12). For the first phase of repairs, the plastic sheeting from the roof was integrated with the new membrane in lieu of removing parts of the roof system.

Following the repairs, we performed a second blower door test using the same parameters as our initial test. We measured a leakage rate of 5.445 L/s/m^2 (0.239 ft^3/min/ft^2) (at a pressure differential of 75 Pa [0.3 in. of water]). This represented approximately a 25% reduction in airflow through the building enclosure. Although this was a reasonable improvement, the building occupants reported new staining on the exterior siding during the first few months of the following winter. In response to these reports, we performed an additional IR scan of the building to locate the contributing air leaks. Our scans showed that the "hot spots" due to air leakage at the main roof eaves were greatly minimized by the repairs but that new hot spots had developed in other areas of the building. This was consistent with our expectation that sealing the primary airflow paths in the enclosure may make the secondary airflow paths more problematic. The magnitude of leakage below some of the windows (which were not addressed in Phase 1) had also increased.

Since air will naturally flow through the path of least resistance, the majority of air leakage occurred through the large air barrier gaps at the roof eaves, which offered relatively little resistance, rather than through smaller gaps that offered greater resistance to airflow. Our IR scan showed that air leaks in many areas of the building, including flat roof-to-wall intersections and some gable end details, had become "activated" by sealing off the primary airflow path at the eaves. The new hot spots that we found during our scan corresponded to the new locations of staining reported by the occupants.

Figure 12 *Initial repairs at roof eaves to address primary air leakage path.*

Following the second IR scan, the option of modifying the mechanical system to maintain a slight negative pressure within the building was discussed. Though this is often dismissed as an option for museums due to the issue of contaminant control, the building owner was amenable to exploring this option due to the nature of the museum collections (typically constructed of durable materials such as glass, metal, and plastic, and generally part of traveling collections that would spend only a few weeks in each museum). Furthermore, our investigations to date showed that the majority of air leakage occurred in the exterior walls near the level of the attic. Since the attic (as well as the exterior walls) functioned as a return air plenum, outside air that is drawn through gaps in the air barrier will naturally flow into the mechanical system returns and through the air filtering system prior to being introduced into the main building spaces.

To evaluate the effectiveness of this option, we worked with the building mechanical engineer to temporarily rebalance the mechanical system to maintain a negative pressure within the building. With the building in "negative" mode, we performed a third IR scan of the exterior of the building. This scan, when compared to previous two scans, confirmed that all of the hot spots on the exterior of the building were caused by air leakage through the enclosure (as opposed to thermal bridging or other heat loss phenomena). We are currently working with the building owner and mechanical engineer to implement a permanent control scheme for maintaining negative pressure, accounting for phenomena such as wind and stack pressures that can affect the pressure balance of the building. Although not acceptable for all cases, the specifics of this museum made negative pressure a cost-effective method of controlling airflow-induced condensation without extensive repairs to the building enclosure.

LESSONS LEARNED

Our work at the above projects has illustrated several key points regarding air barriers in high humidity buildings. These are summarized below:

- Due to the increased risk of condensation in the building enclosure, especially in cold climates, high humidity buildings demand a much higher level of air barrier quality (both design and construction) than typical buildings. In many cases, interior air barriers can be more appropriate than exterior air barriers for isolating humidified environments.
- When performing value engineering of air barrier options, all parties must be made aware of the potential consequences of those decisions. In Case 2, the decision to switch to polyethylene sheeting without further review of the resulting difficulty of sealing the roof/wall intersection contributed to the primary air leaks at the roof eaves.
- Qualitative investigation of air barrier assemblies and systems can be performed quickly and efficiently using IR thermography.
- Quantitative measurement of air leakage using blower doors can be used to directly calculate the effectiveness of air barrier repairs and determine how readily the HVAC system can be adjusted to control pressure and reduce leakage.
- Due to the complexity of building air barrier systems, investigation and repair of those systems must be performed in several stages that may span over the course of months or even years. While complete removal of cladding and roofing systems can allow for inspection and repairs to these air barrier materials, components and assemblies at one time, the cost and level of disruption to the building occupants associated with such repairs is rarely acceptable to building owners or architects.
- When engaging in partial repairs to existing air barrier systems, building owners should be cautioned to expect that secondary air leaks may be "activated" by eliminating leak paths through the primary air barrier.

CONCLUSIONS AND RECOMMENDATIONS

The potentially severe problems associated with air leakage in high humidity buildings warrant additional time and effort during both design and construction. Based on the information presented in this paper and our experience with high-humidity buildings, we have the following recommendations for designing air barriers in these types of buildings:

- **Start Early:** Designing an air barrier system involves much more than specifying individual products and components and listing requirements. All parties, including the mechanical engineer and the general contractor, must be aware of the level of coordination necessary to ensure a successful installation. Involving the general contractor early in the process is especially important, since he will be responsible for coordinating the multiple subcontractors required for installation. Each subcontractor must be made aware of the overall construction of the air barrier details, including the proper sequencing of installation, even if they only play a small role in the installation.
- **Details, Details, Details:** As previously discussed, a perfectly airtight window installed in a poorly constructed wall will offer little benefit to the whole system. Designers must provide details for integrating the air barrier materials and assemblies at critical junctions (as discussed under "Continuity between Air Barrier Elements"). Isometric details of complex transitions are often necessary, especially at window and door openings. The complexity of air barrier systems makes the practice of "letting the contractor figure it out" highly inappropriate.
- **Beware of Value Engineering:** The "value engineering" of air barrier systems must be carried out with caution. As a system, the air barrier cannot be expected to perform adequately when specific materials and components are replaced and eliminated without due consideration to the system as a whole. Designers must make cost-conscious building owners aware of the potentially severe consequences of value engineering an air barrier system.
- **Watch it Get Built:** In the planning phases, designers must stress the importance of construction monitoring to ensure that air barrier assemblies and the system are installed as designed. This includes setting up a budget for construction phase services. Although it is not practical to review every detail of the construction, reviewing critical details early in construction can go a long way towards ensuring quality construction. Mock-ups of critical details are also helpful for coordinating between trades and setting standards of quality at the beginning of a project.
- **Test the Installed System:** Testing of the air barrier is another issue that should be discussed during the design phase, to avoid it being rejected later in the project due to the associated (and possibly unexpected) cost. Whole building airtightness testing combined with IR thermography can be used to verify air barrier installations as well as locate defects in the system. Depending on the construction of the building, it may make sense to perform testing before air barrier components are concealed by cladding materials or interior finishes. Leaving the air barrier exposed will greatly simplify the location and repair of defects.

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