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Performance and preservation requirements at a Frank Lloyd Wright Modern icon inspired the development of a thermally broken steel frame for insulated glazing.

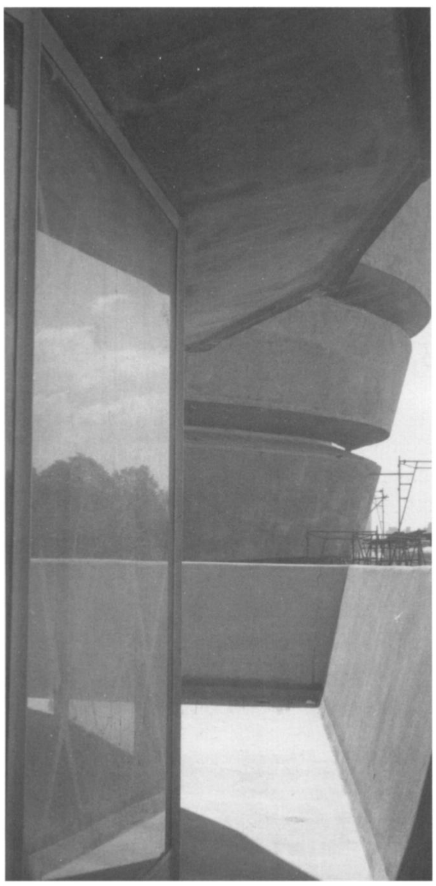

Fig. 1. Fourth-floor steel-frame glass walls during construction, Monitor building, Guggenheim Museum, New York, N.Y., photograph c. 1958. Photograph by William Short, copyright the Solomon R. Guggenheim Foundation.

Introduction

The original Solomon R. Guggenheim Museum in New York City, Frank Lloyd Wright's masterpiece completed in 1959, is a combination of two well-defined structures known as the Monitor and the Rotunda, which complement each other both functionally and aesthetically. The Rotunda is the spiral exhibition space for which the Guggenheim — if not Wright himself — is better known worldwide. In Wright's own words, the Monitor

> was a feature intended for use of the operating personnel of the museum for the amenities of the people who man it day by day and the visitors to the trustees of the museum and their friends. A place for social occasions and propaganda. A place where the amenities could have a place in unique and liberal circumstances. It looks the part and is well adapted to its function.[1]

To fulfill his vision, Wright designed the Monitor as independent levels connected to the Rotunda ramps, with one end of the two upper floors enclosed by polygonal, floor-to-ceiling, glazed enclosures leading to perimeter balconies.

The latest version of the project specifications, issued in 1956, called for a cold-rolled-steel frame system for the glass walls at the Monitor. The original glass walls[2] of the Monitor were manufactured by Henry Hope and Sons in the UK and made of a single-glazed, uninsulated, galvanized-steel frame system (Fig. 1). During construction, the steel finish was discussed as being of a "silver or steel color."[3] Unlike the Gunite walls at the Rotunda ramps, the Monitor's glass walls convey a sense of transparency and extroversion suitable to the non-exhibition spaces they were designed for — and convey Wright's vision of organic architecture, where a building embraces, rather than separates, the indoor and outdoor environments that it is meant to demarcate.

The industrial appearance of this window system, which had remained relatively unchanged since the last decades of the nineteenth century when cold-rolled steel was first used, was completely transformed at the Guggenheim, thanks to Wright's imaginative design for the Monitor's glass walls. Wright combined fixed units and outswing casements on the upper floor and a more elaborate array of inoperable units and casements with horizontally pivoted scallop-shaped transoms at the floor below.

Existing Conditions

By late 2004, at the outset of the recently completed conservation work, the Monitor had undergone several alterations and was no longer used for its original purpose. During the last renovation and addition, dating to 1992, the extent of the original glass walls was reduced to accommodate the new limestone-clad tower designed by Gwathmey Siegel & Associates Architects. At the same time, the original interior partitions in the Monitor were removed, and the space within the original glazed enclosures was dedicated to exhibition display as part of the multistory Thannhauser gallery.

Field evidence indicated that the original galvanized-steel framing of the glass walls was in good condition, showing no sign of deterioration. By traditional preservation standards, they would have been deemed sound, original historic fabric to be retained. During the winter, however, water vapor from warm, humidified indoor air condensed on the colder surfaces of the uninsulated glass panes, steel frames, and mullions (Fig. 2). Under extreme winter conditions, the museum's indoor environmental targets (70°F ± 2°F dry bulb, 50 to

Fig. 2. Seasonal condensation at original fourth-floor interior steel-frame glass walls, photograph 2005. This and all other photographs by Angel Ayón, WASA/Studio A, unless otherwise noted.

55 percent relative humidity, not to fluctuate more than 1 to 2 percent in 24 hours, with an unacceptable range of below 42 percent and greater than 60 percent relative humidity and no sudden spikes)[4] allowed condensation to freeze and form icicles along the steel frames. To a lesser extent, similar condensation occurred during the summer, as the outdoor atmospheric water vapor condensed on the colder, exterior glass surfaces of the Thannhauser gallery.

Such seasonal condensation compromised the stability of the museum's indoor environment,[5] led to energy loss and increased demand for air-conditioning, imposed greater heating and dehumidification loads on the building's mechanical equipment, impaired indoor-outdoor visibility, and rendered the Thannhauser gallery unfit for exhibition display during cold seasons.

In the past, the museum staff had implemented a number of tests to evaluate the suitability of several repair approaches that would address the condensation while retaining the original historic metal fabric.[6] As a result, three of the four original steel-frame double doors on the fourth floor of the Thannhauser gallery had been replaced with insulated-glass (IG) units. A thin, vertical wood strip was adhered to the interior glass surface in an attempt to imitate the appearance of the missing doors when closed. The lack of authenticity implicit in this solution became a concern, as it attempted only to replicate the interior appearance of the original doors and not their operability and exterior appearance.

On the third floor of the Thannhauser gallery, new exterior storm windows with IG units had been installed at select locations, adjacent to the exterior face of the existing single-glazed enclosure. The steel frames encasing the new units increased the original sightlines, modified the exterior appearance of the glazed enclosure, and overshadowed its distinctive semicircular transom pattern (Figs. 3 and 4).

The insertion of IG units during the tests reduced condensation on the glass surfaces, if not eliminating it completely. The shallow glazing pockets of the original steel frames, however, afforded insufficient clearances to install IG units according to current industry standards. The proximity of the IG units to the existing frames had the potential to compromise the integrity of their edge seals and void the fabricator's warranty.

In addition to low-performing glazed enclosures, windows, and skylights, the failure of exterior coatings and cracking of the concrete substrate, combined with aging building systems, required extensive research on suitable repair solutions by a multidisciplinary team. The final scope of work included upgrading building systems and exterior-wall assemblies, removal of exterior coatings, concrete repair and recoating, and skylight and window replacement.[7]

Intervention Approach

Designated as a landmark at the local, state, and national levels, the Guggenheim is a significant example of Modernism, with both interior and exterior landmark designations. Any intervention on the building had to be guided by a well-defined set of principles specifically crafted for this structure.

The intervention approach was conceived by WASA/Studio A in the spirit of the stipulations set forth in the U.S. Secretary of the Interior's Standards for the Treatment of Historic Properties, as well as in other international preservation documents, including the 1964 Venice Charter for the Conservation and Restoration of Monuments, the 1979 Australia ICOMOS Burra Charter (revised in 1999), the 1994 Nara Document on Authenticity, and other relevant documents underlying the theory and praxis of historic preservation to date.

The principles for intervention included retaining original materials; retaining changes that occurred over time; preserving distinctive features; repairing rather than replacing, where possible; replacing in kind, if necessary; avoiding radical changes during work designed to meet current code and energy requirements; ensuring that treatments were not injurious; and ensuring that new work is reversible and differentiated from the historic building fabric.

Fig. 3. Exterior view of existing original third-floor steel-frame glass walls, photograph 2006.

Fig. 4. Exterior view of storm window with insulated-glass units installed during a c. 1994 in-house retrofit, photograph 2006. The exterior glazing obscured the original steel frame.

This preservation philosophy guided the project team's responses to the complex challenges posed by Wright's building. For the exterior glazed enclosures, that meant considering several options to refurbish the original steel-frame glass walls. These options followed two main approaches: refurbishment and replacement.

Table 1. Repair and Replacement Options with Description

ID*	Description and Comments
A0	Original uninsulated steel-frame construction, single glazing. Unacceptable condensation resistance.
A4	New commercial steel-frame window by manufacturer 1 with custom thermally broken mullion. Thermal conductivity of steel-frame window is 50 W/mK. Commercial windows are not sold with a thermal break.
A5	New commercial steel-frame window by manufacturer 2 with custom thermally broken mullion.
A6	New aluminum frame with thermal break in all elements. The extrusions are designed to replicate, to the extent possible, the profiles of the original steel-frame elements.
A8 (b)	New insulated-glass unit with inside glazing having a flange that extends beyond the glazing frame. The extended glazing is mounted in the existing single-pane location. Steel trim and rubber spacer are used to build out the frame at the exterior.
A9	Two-piece aluminum cover installed over the interior of the existing steel frame. The cover includes two thicknesses of insulating material (Pyrogel). The original mullion and frame assembly is left intact. No interior insulation on the mullion. IG unit with ½-inch air space.
A9-a	Same as A9, but with a combination of insulation and metal cover over the interior of the mullion.
A9-b	Same as A9, but with a 1/16-inch semi-insulating coating (0.9 W/mK thermal conductivity) applied to the interior of the mullion.
A10	Same as A9, except with ¾-inch (1.2 inch total thickness) IG unit.
A12	Original frames cut longitudinally and refastened with welded or bolted bridges to accommodate an IG unit with ½-inch air space.

* The IDs used to label each option are consistent with those used during the project research. The IDs of some options representing slight modifications of those shown on the table are omitted for clarity.

Upgrade Options

More than a dozen options were considered to address the undesirable effects of seasonal condensation. The pros and cons of each approach were analyzed. Emerging nanotechnologies, such as thermal-protection coatings, insulating blankets, and heated glass, were included in the study (Table 1). The selection criteria to determine the best approach included both optimal performance and preservation appropriateness. Performance was evaluated using models devised by William B. Rose & Associates, Inc., utilizing software by the Windows and Daylighting Group from Lawrence Berkeley National Laboratory (LBNL).

Method

The overall method for determining the appropriateness of a glazing system for the third- and fourth-floor Thannhauser enclosures at the Guggenheim consisted of examining the condensation resistance of the glazing system. Three sites of possible condensation were studied:

- center of the glass, which depends entirely on the glass specification
- frame, which is independent of the glass specification but depends on the section and material properties of the supporting frame elements
- edge, where the frame meets the glass.

Software

The study made use of public domain software Therm 5.1 and Windows 5.1, developed at Lawrence Berkeley National Laboratory (LBNL). The latest version of programs is available for downloading from the laboratory's Web site.[8]

Therm 5.1 is a 2-D heat-transfer modeling program. It creates a mesh in two dimensions and calculates conductive and radiant effects along that mesh. It also applies air-film resistances at the interior and exterior. It is used to characterize heat flow and the resulting temperatures in the frame members, including sill, jamb, head, and dividers. Convection is accounted for in the selection of orientation of the frame members and the effect of gravity on air films as a function of surface temperature. Drawings of details of the frame elements are traced into the program, and thermal-transfer properties are selected from menus or entered on a case-by-case basis.

Windows 5.1 is a window-performance-characterization program. It uses the properties of frame elements derived from Therm. It permits glazing systems to be built up of individual panes with selectable properties. It calculates the overall U-factor and the condensation resistance (CR) of window-frame units, among other parameters.

The National Fenestration Rating Council (NFRC) has developed a condensation index (CI) to allow relative rating of windows for condensation resistance, presented in Standard NFRC 500, which is downloadable from the NFRC Web site.[9] The CI from NFRC corresponds to the CR used in LBNL Windows software. The CR is a unitless number between 1 and 100, with a higher number being less likely to form condensation. The standard, and the software that supports the standard, reports CR for three indoor levels of relative humidity — 30 percent, 50 percent, and 70 percent — but it cautions against interpretation of perfect assurance against condensation for any CR value. NFRC uses 0°F as the outdoor standard temperature and 70°F for indoors.

In the Guggenheim glazing project, the software was used to determine the CR of both existing and proposed glazing systems. The default NFRC boundary conditions were used. The study led to an investigation of actual surface-temperature estimates, although LBNL research has shown a good correlation between CR results and the likelihood of condensation formation.

The initial target value for CR of the glazing system is 35. This value is suggested as a threshold value in Windows software, but it is open to interpretation depending on interior finishes and exterior conditions. There are graphic limitations to the software, including the fact that angled constructions cannot be shown. Thus, the glazed enclosures at Thannhauser are shown and modeled as if they were straight. The physical effect of this modification is considered minor.

The air film in contact with the surface of the frame and glazing provides thermal resistance. The LBNL software

Table 2. Summary of Condensation-Resistance Values for All Options

Options	Descriptions	Condensation Resistance							
		Overall CR	CR at Glass	CR at Edge	CR at Frame	Overall U-Factor	U-Factor at Glass	U-Factor at Edge	U-Factor at Frame
Existing Conditions: Third Floor									
A0.1	Existing glazed enclosure at third floor, Thannhauser gallery	13	12	12	16	1.08	1.04	1.01	1.82
Existing Conditions: Fourth Floor									
A0.2	Existing glazed enclosure at fourth floor, Thannhauser gallery	13	12	12	15	1.08	1.04	0.81	2.6
Repair: Exterior									
A1.1	New exterior insulating steel cover	22	69	48	22	0.424	0.255	0.364	1.18
A1.2	New exterior insulating system	35	64	49	35	0.476	0.319	0.386	1.145
Repair: Interior									
A1.3	New interior insulating steel cover	43	70	49	43	0.401	0.255	0.347	1.023
A1.4	New snap-on interior insulated metal cladding with 1 1/4-inch IG unit	24	49	36	24	0.618	0.46	0.521	1.356
A1.5	New snap-on interior insulated metal cladding with 1-inch IG unit	26	69	45	26	0.463	0.255	0.353	1.417
A1.6	Repair with new 1-inch IG unit and new steel glazing bead	16	100	31	14.7	0.46	0.26	0.62	1.35
A1.7	Repair with new 1-inch IG unit and grey gasket	19	69	46	19	0.45	0.255	0.367	1.27
A1.8	Repair with new 5/8-inch IG unit and thermal blanket	23	49	23	29	0.602	0.458	0.612	1.265
A1.9	Repair with new 5/8-inch IG unit and existing glazing bead	17	50	37	17	0.618	0.441	0.492	1.44
A1.10	Repair existing windows	13	12	12	16	1.08	1.04	1.01	1.82
A2.1	New custom-made thermally broken aluminum system	43	48	43	45	0.488	0.46	0.499	0.63
Replacement: Steel									
A2.2	New custom-made thermally broken steel system	36	69	52	36	0.362	0.255	0.335	0.773
A2.3	New steel frame system by manufacturer 1	19	69	44	19	0.43	0.255	0.374	1.51
A2.4	New steel frame system by manufacturer 2	17	49	37	17	0.574	0.457	0.525	1.47

allows users to select values for air-film resistance for the various surfaces. In this analysis, the air-film conductance at the interior is selected at 0.58 Btu / (hr ft^2 F). The exterior air film is standard for NFRC analysis at 4.579 Btu / (hr ft^2 F). The difference between these two indicates the anticipated stillness of the air at the respective surfaces — windy at the exterior and relatively motionless at the interior.

Glazing

The CR values for glazing clearly indicate that the existing single-pane glazing is unacceptable and that double-pane or insulated glazing would be required. IG units, with a factory-created hermetic seal between two glass panes, are greatly preferred over the simple application of two panes in the field. This approach, which would have created an exterior "storm window," did not provide assurance against condensation between the existing and the new glass panes.

The IG units shown in this analysis consist of two panes, each 0.225 inches in thickness. The interior surface of the exterior pane (#2 surface) is treated with a low-emissivity coating. For most of the analysis, the space between the panes is 1/2-inch with argon infill. The spacer is designed for low conductivity at the glass edge, using material properties of stainless steel and desiccant. Example A10 is modeled using a 3/4-inch air space rather than 1/2-inch space, with little difference in condensation performance. The use of argon or krypton gas was not modeled. Use of these gases will improve the energy conservation of the glazing system, but since all insulated glazing shows good condensation resistance, its use would not affect the findings of the study.

Heating

The introduction of heating strips into the existing frames was investigated. The goal was to prevent condensation on the existing steel frames, which would have allowed retaining original historic fabric. For this purpose, strips 6 feet long could be introduced into the concealed space inside the existing steel frame, and a circuit could, in principle, be continued through the ceiling, the header, or the kick-plate areas. Controls could be manual on a timer (common with other heating devices); manual on/off; actuated by measured surface conditions; or automatically activated depending on the indoor humidity and outdoor temperature.

It was determined that heating devices should be considered in combination with IG and only if passive condensation control could not be achieved. Communication with manufacturers[10] of heating strips indicated the possibility of

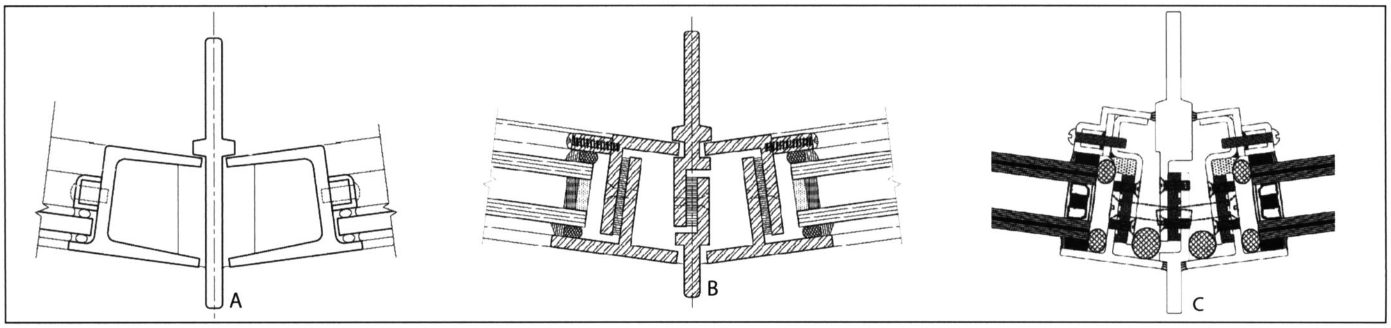

Fig. 5. Typical jamb details. A: Existing steel mullion and frames. B: Proposed thermally improved steel frame and mullion by WASA/Studio A. C: Proposed thermally improved mullion by manufacturer 3. Drawings by WASA/Studio A and manufacturer 3. Not to scale.

the heating elements fracturing in service, which would have had significant maintenance implications. The investigation into heating strips did not proceed any further.

Findings

The results for the pertinent cases studied are presented in Table 2, which shows U-factors and CR values of different elements.

In summary, four approaches to modifications of the Thannhauser glazing were studied:

- new systems
- modifications to the exterior
- modifications to the interior
- splitting and bridging the existing units.

It was assumed that new systems would be either of readily available steel or custom-made aluminum. New steel systems (A4 and A5) may have captured the look and feel of the original; however, the authors were unable to locate any commercially available steel systems with satisfactory condensation resistance. An aluminum system (A6) had good CR performance, but the necessary extrusions would, not surprisingly, require custom manufacture. The main objection to this approach, however, was derived from the performance of similar non-thermally broken aluminum-frame replacement units installed during the 1992 work. Field evidence indicated that these replacement aluminum units, which match the sightlines of the original steel-frame assemblies, exhibited buckling and misalignment as a result of undersizing. Given that the sightlines of a thermally broken aluminum system would have to be larger than those of the original steel-frame glass walls, this solution was deemed unsympathetic to the building's historic image and use of materials, and it was therefore not recommended.

Exterior modifications to the existing glass walls (A8) were deemed possible and likely to be effective; however, the overall glass opening would be slightly reduced, the sightlines increased, and detailing of the necessary glass and steel elements remained to be researched.

Modifications to the interior seemed promising, provided that the mullions would have a thermal break (A9a). Interior cover trims with thermal isolators were developed by WASA/Studio A and William B. Rose & Associates. Making this system work would have required further investigation of new materials, such as Pyrogel insulation and ceramic coatings.

Splitting the frames, the equivalent of providing a thermal break, would leave the interior and exterior in practically the same state as the original while incorporating IG units; however, the handwork could have been laborious; the performance of the resulting product would have been untested; and it would have resulted in a substantial alteration of original material that was not warranted.

Preservation and Constructability Assessment

This part of the study was aimed at providing an assessment of the condensation resistance of the various options under study. The following units were deemed satisfactory: A6, A8, A9b, and A12. Selecting an approach required study of many other parameters. The preservation guidance set forth by WASA/Studio A offered several appropriate criteria. Table 3 presents some of those factors, together with other possible parameters for consideration. The evaluations given in Table 3 are subjective assessments by the authors. They were presented as a means to facilitate assessment by the designers and others, not as a basis for decision making.

Recommendations

Besides performance, the solutions derived from the refurbishment approach had other relevant implications. For instance, this approach would have significantly modified the appearance of the historic metalwork and, to some extent, would have been injurious to original historic fabric in sound conservation state. In addition, options to retain the well-preserved metal work were not fully functional or warrant-

Fig. 6. Mock-up of typical fourth-floor steel-frame glass wall at the testing laboratory, photograph 2007.

Table 3. Response to Preservation and Constructability Criteria[1]

Preservation Criteria	A4, A5	A6	A8	A9, A10	A12
Original materials	No	No	Yes	Yes	Yes
Preserve distinctive features	Medium	Medium	Medium	Yes	Yes
Repair rather than replace	No	No	Yes	Yes	Yes
Treatments not injurious	No	No	No	No	Yes
Reversible	No	No	Yes	Yes	No
Energy Conservation	No	Yes	Yes	Moderate	Yes
Other Criteria					
Installation difficulty	Medium	Medium	Low	Low	High
Difficulty at scallop	High	High	Low	Low	Low
Difficulty at doors	Medium	High	Medium	Low	Low
Fabrication cost	Medium	High	Low	Low	High
Condensation resistance	No	Yes	Yes	Moderate	Yes

1. Authors' subjective estimate

able, and their performance had limited predictability.

Despite the good physical condition of the steel-frame glass walls, its poor performance made replacement the more appropriate upgrade option. For the glass walls, enabling the year-round visibility implicit in the original design intent and upgrading the environmental performance took precedent over the retention of original historic fabric in good physical condition. Accordingly, an unprecedented thermally broken-steel frame system, matching the appearance and sightlines of the original glass wall, was designed by WASA/Studio A and William B. Rose & Associates (Fig. 5).

A set of construction documents for glazing replacement was prepared, including drawings and specifications. The documents outlined the extent of the removal and replacement work, as well as the performance requirements to be achieved during the design, manufacturing, testing, transportation, erection, glazing, and finishing of the work.

The proposed work included replacement of the four operable units at each level, with fixed units matching the general appearance and detailing of the existing ventilators, including replication of the exterior hinges, astragals, and interior bronze hardware. At each level, an operable unit providing access to the balcony was installed at the location where the original glazed enclosures had been shortened to accommodate the 1992 addition.

Laboratory Testing

Given that there was no documented industry standard to use as a reference, innovative construction details were proposed by selected manufacturers during the bidding process (Fig. 6). Two of these manufacturers were retained by the Guggenheim to construct full-scale mock-ups representative of their systems. The mock-ups were designed to include configurations and details matching the existing conditions.

The mock-ups were subject to comparative testing at an independent testing agency. Water infiltration was tested according to *ASTM E2268-04 Standard Test Method for Water Penetration of Exterior Windows, Skylights, and Doors by Rapid Pulsed Air Pressure Difference*.[11] Structural properties were tested per *ASTM E330 Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference*.[12] Thermal performance was tested according to *AAMA 1503-98, Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections*.[13] Air leakage was tested according to *ASTM A283 Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen*.[14]

The mock-ups also afforded an opportunity to assess each system's constructability and appearance. Two additional qualifiers were evaluated for each mock-up. The first related to the cost of manufacturing, delivery, and installation of the new units. The second, and perhaps most subjective qualifier, evaluated the manufacturer's ability to take on the risk intrinsic in engineering, manufacturing, and warranting a system for which there was no precedent in the steel-frame fenestration industry at the time. For the purpose of presenting the results of the comparative analysis in this article, the authors called this less-measurable qualifier "likeability."

The results of the comparative testing summarized in Table 4 show that there was no significant difference between either manufacturer's system regarding air leakage, thermal transmittance, and deflection as the result of lateral forces. The water infiltration documented in one of the specimens was attributed to the lack of weep holes, an easily surmountable shortcoming.

Given the uniformity of the laboratory-testing results and the visual and cost similarities between both systems, the selection of the successful manufacturer pivoted around the more intangible concept of "likeability." The successful manufacturer's stated confidence in its ability to improve the performance of the proposed system, coupled with its willingness to take on risk and work with the museum on successfully completing the new system's design and installation at a fixed, competitive price, paved the way for the contract award.

Scope of Work

The replacement work involved the removal of all the existing steel-frame

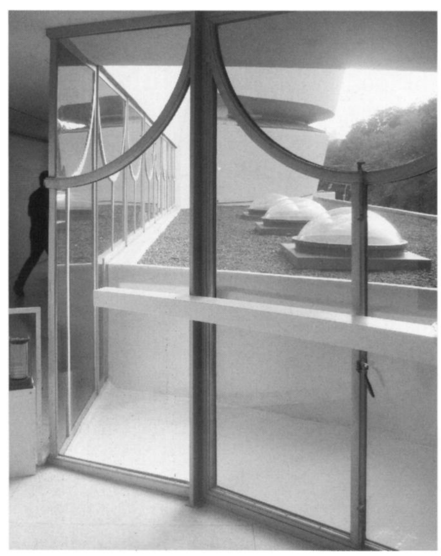

Fig. 7. Interior view of new thermally broken steel-frame glass walls installed on the third floor, photograph 2009.

Table 4. Results of Comparative Testing between Thermally Improved Steel-Frame Mock-ups

Test Method	Test Pressure	Manufacturer 1	Manufacturer 3
Air leakage	6.24 lbf/sq. ft	0.01 scfm/ft^2	0.01 scfm/ft^2
Water-penetration resistance	6.24 lbf/sq. ft	No water leakage in specimen	Water leakage in specimen
Uniform load deflection	30 lbf/sq. ft	0.063-inch deflection in positive load, 0.092-inch deflection in negative load	0.010-inch deflection in positive load, 0.018-inch deflection in negative load
Thermal transmittance U	Btu/hr ft^2 °F	0.51	0.53
Condensation-resistance factor	N/A	58	65
Cost		High	High
Likeability		Lower	Higher

glazed enclosures at the Thannhauser gallery. Representative samples of the original steel-frame enclosure were retained as part of the museum's collection to ensure archival preservation of such a distinctive original historic feature. The new custom-made steel-frame system, as intended, matches the appearance of the original glazing.

To improve the thermal performance, the spacing of the fasteners bypassing the thermal break was calculated to the minimum required, and the thickness of the concealed thermal break within the system was increased as much as possible. The enlarged neoprene thermal break, which is greater than 5.30 mm (0.210 inch), helps the new system perform similarly to the thermally broken pressure-glazed systems defined in industry standards for aluminum fenestration.[15]

In addition to improved energy performance, the new glazing afforded enhanced light-transmittance reduction, as well as sound and UV protection within a range more suitable to the museum environment (Fig. 7). The interior and exterior appearance was designed to match that of the original as much as permitted by the installation of the new IG units, and it resulted in no significant change to sightlines and general appearance (Figs. 8 and 9).

On the southwest corner of the ground floor, facing the intersection of Fifth Avenue and East 88th Street (not in the Monitor), another original, facetted, glass-wall enclosure with butt joints and perimeter aluminum frame demanded a different solution. At this location, which is part of the designated-landmark exterior facade and Rotunda interior, the insertion of IG units would have addressed the seasonal condensation experienced during extreme weather conditions. This solution, however, would have modified the appearance of the frameless glass joints, barely 3/8 inch wide. To avoid compromising the enclosure's architectural character, WASA/Studio A proposed to install heated-glass units.

Heated glass is an emerging technology where a transparent coating adhered to the glass is connected to a low-voltage power source, uniformly heating the glass surface through a patented control unit. Through this proprietary process, the glass temperature can be adjusted manually or automatically anywhere from 75°F to 350°F.[16] At the time of the writing of this article, the selected heated-glass manufacturer was pursuing UL certification of the new controller required for the relatively large size of this application, also to be installed on a thermally broken steel frame.

Final Considerations

While conserving buildings from the recent past, the need to upgrade glazed building-envelope systems to meet the performance requirements of new uses might outweigh, on a case-by-case basis, preservation mandates for retaining original, yet low-performing, glazed systems. However, it must be argued that when the upgrade of historic glazed building-envelope systems is required, preservation mandates for in-kind material replacement should be pursued, along with an upgrade of system performance and retention of the original appearance and design intent.

The Guggenheim project revealed a number of conceptual and technical issues that are worthy of mention. For instance, the process for assessing existing conditions and determining the most suitable upgrade option confirmed that clearly defining the preservation approach at the project outset will help to reconcile performance improvement with retention of historic character.

The outcome of the research undertaken for the project revealed that when visual alterations of historic glazing are required, it may be preferable to implement them from the interior in order to preserve the integrity of the building image. Some projects, however, may demand otherwise.

New advances in glass technology afford great advantages to the retrofitting of Modern glazed enclosures. Light transmittance and reflectivity values, however, should be addressed carefully. On-site monitoring, data collection, thermal modeling, investigative probing, materials research, construction of mock-ups, and laboratory and field testing are part of a methodological process through which historic glazed building envelopes should be assessed. Even though project schedules and budgets might pose certain constraints, laboratory and field testing will corroborate the suitability of innovative designs and technologies that, although creative and promising, have no proven performance record. No less important, the air-conditioning adjustments required after installation of the new high-performance glazed enclosure at the museum confirmed that improvements

Fig. 8. Exterior view of new thermally broken steel-frame glass walls installed on the fourth floor, photograph 2009.

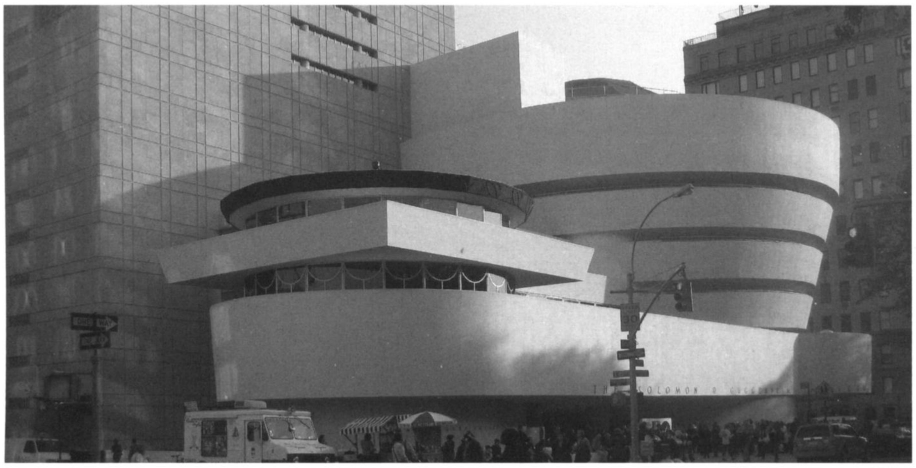

Fig. 9. New thermally broken glass walls after completion of the work, photograph 2009.

to the building envelope, particularly glazed enclosures, should be undertaken prior to resizing the air handlers servicing the adjacent interior spaces.

Regarding thermally broken steel-frame glazed enclosures, the Guggenheim reglazing project revealed the need to minimize attachments through the thermal break, which are necessary for structural strength but undesirable for thermal performance. Thermal breaks should be as continuous and unobstructed as possible, and, of course, the warm side should not be in contact with the cold side. Quality control, from design through construction, is paramount to success. Similarly, workmanship is important, as the successes of the system depend on accurate field documentation, precise metalwork, and installation by skilled glazing mechanics. Lastly, industry standards for the design, testing, and installation of similar systems should be developed, and data on their performance should be collected, analyzed, and published.

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Notes

1. Frank Lloyd Wright to Harry Guggenheim, Dec. 18, 1958, Early Building History Archive, Solomon R. Guggenheim Museum.

2. Unlike many other postwar Modern buildings displaying the so-called "curtain walls" — a glazed or thin-stone-clad enclosure along the perimeter of the building defining its facade and usually visible from the street level — Wright did not place the Guggenheim's glazed enclosures along the perimeter of the museum, and he screened them with balconies. To emphasize this distinction, the authors chose to refer to these glazed enclosures as "steel-frame glass walls" or by the shorter term "glass walls."

3. William H. Short to Frank Lloyd Wright, July 8, 1958, Early Building History Archive, Solomon R. Guggenheim Museum.

4. Memorandum from AKF Engineers, "Temperature / relative humidity monitoring overview – April, May, June 2005," June 27, 2005.

5. Indoor-temperature and relative-humidity measurements were taken at more than 40 locations during the course of this study. A review and summary of the indoor-environment data is beyond the scope of this paper.

6. Carol Vogel, "Not Heat, But Humidity," *New York Times*, Jan. 14, 1994.

7. Angel Ayón, et al., "Preserving a Modern Icon: Recent Work at the Guggenheim Museum," *Docomomo US Newsletter* (Spring 2009): 9–11.

8. For more information on the LBNL, see www.lbnl.gov (accessed June 2011).

9. For information on the NFRC, see www.nfrc.com (accessed June 2011).

10. A manufacturer with an extensive list of heating devices is found at www.watlow.com (accessed Jan. 2006).

11. For *ASTM E2268-04*, see http://www.astm.org/Standards/E2268.htm (accessed June 2011).

12. For *ASTM E330*, see http://www.astm.org/Standards/E330.htm (accessed June 2011).

13. For *AAMA 1503-98*, see *AAMA Publication 1503-98: Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections* (including May 4, 1998, Errata and December 1, 1999, Addendum).

14. For *ASTM A283*, see http://www.astm.org/Standards/A283.htm (accessed June 2011).

15. U.S. National Fenestration Rating Council Inc., *NFRC 100: 2001, Procedures for Determining Fenestration Product U-factors*, 2nd edition, Nov. 2002, http://www.nfrc.org/documents/NFRC_100-2001.pdf (accessed Dec. 8, 2009).

16. Architectural heater glass by Thermique, http://www.thermiquetechnologies.com/architectural.html (accessed, Dec. 8, 2009).

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