Glazing Upgrade at Frank Lloyd Wright's Solomon R. Guggenheim Museum

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ABSTRACT

The paper presents more than a dozen options considered to address the undesirable effects of seasonal condensation at Frank Lloyd Wright’s Guggeneim Museum in New York. These options followed two main approaches, repair and replacement. The pros and cons of each approach will be presented, as well as the selected replacement option with an uprecedented custom-made thermally-broken steel frame system matching the exterior appearance of the original glazing. The energy models devised for the proposed replacement systems, using software by the Windows & Daylighting Group from Lawrence Berkeley National Laboratory, are presented. Innovative construction details prepared by the Architect and selected manufacturers to build the thermally broken systems are discussed, as well as the results of the comparative testing of such systems.

Keywords: Fenestration Upgrade, Existing Buildings, Thermal Upgrade, Case Study Hygric and Thermal Upgrade.

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Introduction

The original Solomon R. Guggenheim Museum (SRGM) in New York City, Frank Lloyd Wright's masterpiece completed in 1959, is a combination of two well-defined structures complementing each other both functionally and aesthetically. Known as the Monitor and the Rotunda, the latter is the unique 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 this 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, glass walls leading to perimeter balconies (fig. 1).

Fig. 1: Solomon R. Guggenheim Museum, New York, NY (ca. 1959) © William B Shot, Solomon R Guggenheim Foundation.

Fig. 2: Original single-glazed steel-frame glazed enclosure at the Guggenheim Museum. (ca. 1958) © William B Shot, Solomon R Guggenheim Foundation.

The original glass walls, manufactured by Henry Hope's & Sons in the UK, were a single-glazed, un-insulated, galvanized steel-frame system (fig. 2).

Fig. 3: Existing single-glazed steel-frame glazed enclosure at the Guggenheim Museum. (2005) © Angel Ayón, WASA/Studio A.

Unlike the Rotunda, the glass walls convey a sense of transparency and extroversion suitable to the non-exhibition spaces they were designed for —and to Wright's vision of organic architecture, where a building embraces, rather than separates, the indoor and outdoor environments that it is meant to demarcate (fig. 3).

Existing Conditions

Like most museums, the SRGM was humidified in winter. The mean annual RH was about 50%. The variation in temperature and humidity in the building—seasonally, spatially and diurnally—is beyond the scope of this paper.

By late 2004, at the outset of conservation work recently completed at the Guggenheim, the Monitor had undergone several alterations and was no longer used for its original purpose. During the last renovation, dating from 1992, the interior partitions were removed and the space within the original glass walls was dedicated to exhibition display as part of the Thannhauser gallery.

The original galvanized steel framing of the Guggenheim's glass-walls were in good condition, showing no sign of deterioration and, by traditional preservation standards, would have been deemed as sound, original historic fabric to be retained. During the winter, however, water vapor from warm, humidified, indoor air condensed on the cold surfaces of the un-insulated glass panes, steel frames and mullions (fig. 4). To a lesser extent, similar condensation occurred during the summer, as the outdoor atmospheric water vapor condensed on the cold exterior glass surfaces of the Thannhauser galleries.

Fig. 4: Condensation at exterior glazed enclosure. (2005) © Angel Ayón, WASA/Studio A.

Such seasonal condensation compromised the stability of the indoor museum environment;, impaired indoor-outdoor visibility; created wet spots posing a traffic hazard, and lowered the RH in some locations to levels 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 existing condensation while retaining the original historic metal fabric.[2] As a result of testing procedures, three out of four of the original steel-frame double doors at 4th floor Thannhauser had been removed and replaced with insulated glass (IG) units. A thin vertical wood strip adhered to the interior glass surface attempted to imitate the appearance of the missing doors when closed. The lack of authenticity implicit in this solution became a concern, as it only attempted to replicate the interior appearance of the original doors, and not its operability and exterior appearance.

At the 3rd floor Thannhauser, new IG units had been installed at selected locations, adjacent to the exterior face of the existing single-glazed enclosure. The steel frames encasing the new insulating glass increased the original sightlines, modified the exterior appearance of the glazed enclosure and overshadowed its distinctive semicircular transom pattern (fig. 5).

Fig. 5: New IG unit on steel- frame in front of original glazed enclosure.
(2007) © Angel Ayón, WASA/Studio A.

The insertion of insulated glass units in the aforementioned tests rendered positive results to reduce condensation on the glass surfaces, if not eliminating it completely. There was no observed condensation, but observations were occasional and intermittent. However, the shallow glazing pockets of the original steel frames provided insufficient space 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 warranties.

In addition to poorly-performing glazed enclosures, windows and skylights, failure of exterior coatings and cracking of the concrete substrate above and below the windows, combined with aging building systems, required extensive research of suitable repair solutions by a multidisciplinary team. The final scope of work included upgrade of building systems and exterior wall assemblies, removal of exterior coatings, concrete repair and recoating, skylight and window replacement.[3]

Intervention Approach

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

The principles for intervention included (1) retaining original materials; (2) retaining changes that occurred over time; (3) preserving distinctive features; (4) repairing rather than replacing, and replacing in kind if necessary; (5) avoiding radical changes in work designed to meet current code and energy requirements; (6) ensuring that treatments are not injurious; and (7) ensuring that new work is reversible and differentiated from historic building fabric.

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 Guggenheim's original steel-frame glazed enclosures. These options followed two main approaches, repair and replacement.

Upgrade Options

Many options were considered to address the undesirable effects of seasonal condensation. Some options were given only minimal consideration—others were given more. The pros and cons of each approach were considered (including as-yet-unavailable nanotechnologies) such as thermal-protection coatings, insulating blankets and heated glass. The selection criteria to determine the successful approach included both optimum performance and preservation appropriateness. Performance was evaluated using heat transfer models devised by William B. Rose & Associates, Inc. utilizing software by the Windows and Daylighting Group from Lawrence Berkeley National Laboratory.

Method

The overall method for determining the appropriateness of a glazing system for the Thannhauser 3 and 4 areas of the SRGM consists of examining the condensation resistance of the glazing system. Three sites of possible condensation are studied:

- Center of glass, which hinges entirely on the glass specification

- Frame, which is independent of glass specification, but depends on the section and material properties of the supporting frame elements, and,

- Edge, the glazing zone where the frame meets the glass, with the glass impacted by heat transfer through the frame.

Software

This study made use of public domain software THERM 5.1 and WINDOWS 5.1, developed at Lawrence Berkeley National Laboratory (LBNL). The programs are available for downloading from the lbnl.gov web site.

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. The user applies air film resistances at the interior and exterior. It is used to characterize heat flow, and the resulting temperatures, in frame members including sill, jamb, head and dividers. Convection can be accounted for in the selection and orientation of the frame members, and the effect of gravity on air films as a function of surface temperature. Drawings of frame element details are traced into the program, and thermal transfer properties are selected from menus or entered on a case-by-case basis.

WINDOW 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 overall U-factor and Condensation Resistance (CR).

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 website. 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 which supports the standard, reports CR for three indoor levels of relative humidity—30%, 50% and 70%, but it cautions against interpretation of perfect assurance against condensation for any CR value. NFRC uses a single outdoor temperature as the design standard (0ºF). Where colder outdoor conditions dictate greater condensation resistance, a higher CR rating can be used rather than a required recalculation of the glazing system properties at different outdoor temperatures.

In the Guggenheim glazing project, the software was used to determine the CR of both existing and proposed glazing systems. The study led to an investigation of actual surface temperature estimates. The means of attachment of several temperature sensors that were put in place during a short study led internally inconsistent results, so those measured findings are not reported here.

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

Boundary Conditions

The boundary conditions used for the study were 70ºF indoor temperature and 0ºF outdoor temperature. An outdoor temperature of 0ºF is the basis of the LBNL software. It was judged to be an acceptable design value following a review of several New York City weather tapes. The desired (unitless) condensation resistance number that results from the analysis may be selected as higher or lower depending on the anticipated severity of the outdoor climate.

The LBNL software provides condensation resistance output values at three relative humidities: 30%, 50% and 70%. A common target value for a relative humidity in a museum is 50%. There is a growing call for seasonal ramping of museum humidity—lower during winter (c.f. ASHRAE *Handbook Applications 2007*, Chapter 21 "Museums, Galleries, Archives and Libraries"). The results of this analysis are presented with 30% and 50% values. If the wintertime humidity is expected to be at some value between 30% and 50%; the CR results may be roughly interpolated.

The air film in contact with the surface of the frame and glazing provide thermal resistance between the indoor air temperature and the glass surface. The LBNL software allows users to select values for air film resistance for the various surfaces. In this analysis, the air film resistance at the interior is selected at 0.58 Btu / (hr ft^2 F), and the exterior air film at 4.579 Btu / (hr ft^2 F) for consistency with NFRC analysis (Air Film I). The difference between these two indicates the anticipated stillness of the air at the respective surfaces—windy at the exterior and moderately still at the interior.

Materials

Materials in window units have differing thermal conductivity. Table 1 shows some common conductivity values. Metals are very conductive, thus the importance of achieving a thermal break.

Material	**W/m-K**	**Btu / (hr-sf-F)***
Aluminum	237	136.9
Butyl rubber	50	28.9
Expanded polystyrene	17	9.8
Felt	1	0.578
Ceramic coating	0.900	0.522
Foam rubber (backer rod)	0.400	0.231
Glass	0.240	0.139
Hardwood	0.230	0.133
Neoprene	0.230	0.133
Plexiglass	0.210	0.121
Polysulfide	0.200	0.116
SRGM mastic (assumed)	0.160	0.092
Steel, buffed stainless	0.060	0.035
Steel, cold rolled	0.050	0.029

Urethane, polyurethane	0.038	0.022
Pyrogel	0.016	0.009

Table 1: Thermal conductivity values for common window components.
*Primary source: ASHRAE Handbook *Fundamentals 2005*, Ch. 26.

Pyrogel, which is included on the list, is a product of "nanotechnology" that at the research outset (Fall 2005) had been recently introduced by the Aerogel company, makers of superinsulating foam. Its thermal properties, as advertised, are exceptional. The product is sold as a blanket, with no structural support of its own.

Glazing

Results below indicate that The CR values for glazing clearly indicate that the existing single-pane glazing is unacceptable and double-pane or insulated glazing (IG) is required. Insulated glazing, with a factory-created hermetic seal between two glass panes, is greatly preferred over the simple application of two panes with an unsealed airspace in the field. It is virtually impossible to guarantee freedom from condensation, except in the presence of an ideal set of conditions at the glazing frame.

The IG units shown in this analysis consist of two panes 0.225" in thickness (nominal 0.25 in.). The interior surface of the exterior pane is treated with a low-emissivity coating. For most of the analysis, the space between the panes is ½". The stainless steel spacer is designed for low conductivity at the glass edge, and it contains a desiccant. Example A10 is modeled using a ¾" air space rather than ½", 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, the use of these gases would not significantly affect the findings of the study.

Coating

For most of the analysis, there is no thermal property assigned to the surface coating. Example A9c makes use of a ceramic material (Metco 205NS PreAlloyed Zirconia powder by Sulzer Metco) used in industrial heating and cooling. (The authors are not familiar with the product.) Product reference sheets claim a thermal conductivity of 0.9 W/mK. This conductivity is like that of brick—not outstanding but far better than metals. Example A9c uses this material in a 1/16" thickness.

Heating

An investigation into the introduction of heating strips into the existing frames was undertaken. Strips, 6' in length, could be introduced into the concealed space inside the existing Hopes steel frame, and a circuit could, in principle, be continued through the ceiling area or the kickspace area. Controls could be manual on a timer (common with other heating devices), manual on/off, actuated by measured surface conditions, or activated by logic involving indoor humidity and outdoor temperature.

Communication with manufacturer of heating strips indicated the possibility of the heating elements fracturing in service, which may have significant maintenance implications. The investigation into heating strips did not proceed further.

Findings

Results

The results for the pertinent cases studied to date are presented in Table 2 below. They are shown in detail in Appendix A and Appendix B. Appendix A provides a page for each option. Each page shows U-factors of different elements, condensation resistance values and a section of the divider with isotherms imposed. U-factors are measures of thermal conductivity. Low numbers reflect low conductivity of heat, thus high resistance to heat flow. A U-factor less than 0.5 indicates an overall thermal resistance, including air films, greater than R-2 (i.e. 2 hr-ft^2-degF / Btu). The cases shown in Appendix A also show calculated values of Condensation Resistance: overall, at 30% relative humidity, at 50% relative humidity, and at the glass, frame and edge (where the frame meets the glass).

Interpreting CR values requires judgment arising from use. As a general guide, the LBNL website recommends values above 35 for the middle states of the US. Given the information available, the, a CR of 35 forms an appropriate target value for the Guggenheim. If the interior humidity is to be 50%, then it is recommended to use the 50% CR values for frame, glass and edge. If the wintertime humidity will be permitted to drop below 50% during winter, then a CR value interpolated between the 30% value and the 50% value is most appropriate. Appendix B contains the reports that THERM and WINDOW software provides as output.

Option	**CR**	**Description and Comments**
A0	17	Original uninsulated steel-frame construction, single glazing. Unacceptable condensation resistance
A4	17	New commercial steel-frame window by Manufacturer #1 with custom thermally broken mullion. Thermal conductivity of steel-frame window is 50 W/mK. Commercial steel windows are not sold with a thermal break. Unacceptable condensation resistance.
A5	18	New commercial steel-frame window by Manufacturer #2 with custom thermally broken mullion.
A6	43	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. Acceptable condensation resistance.
A8 (b)	49	New IG unit with inside glazing having a flange that extends beyond the glazing frame. That 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. Acceptable condensation resistance.
A9	25	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” air space. Unacceptable condensation resistance.
A9-a	41	Same as A9, but with a combination insulation and metal cover over the interior of the mullion. Acceptable condensation resistance.
A9-b	33	Same as A9, but with a 1/16” semi-insulating coating (0.9 W/mK thermal conductivity) applied to the interior of the mullion. Barely unacceptable condensation resistance.
A10	24	Same as A9, except with ¾” (1.2” total thickness) IG unit. Unacceptable condensation resistance.
A12	38	Original frames cut longitudinally and refastened with welded or bolted bridges to accommodate an IG unit with ½” air space. Barely acceptable condensation resistance.

Table 2: Options with description

A0 Original condition

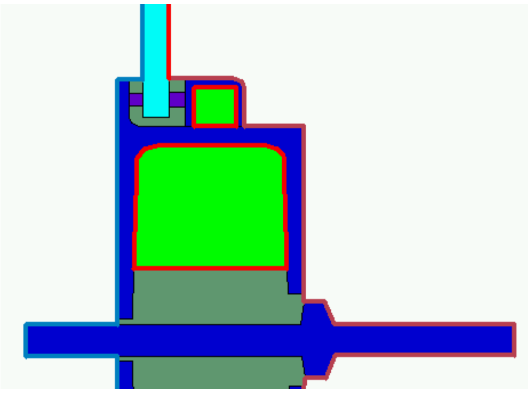

Fig. 6: Thermal modeling of existing single-glazed un-insulated steel frame.

A0. The original steel-frame windows contain rolled steel (blue/dark) for the frame element, the mullion and the stop for securing the window. The glazing is ¼” plate glass. The mastic used to fasten the window in its pocket and the frame element against the mullion were labeled “SRGM mastic” for the purpose of the study (conductivity 0.133 Btu / h-ft-F, similar to Neoprene). Voids are shown in green; they are treated by THERM software for conductive, radiative and convective heat transfer. Experience indicates that condensation occurs on the interior surface of this assembly during cold weather. Overall CR: 17.

A4, A5, A6 New window units

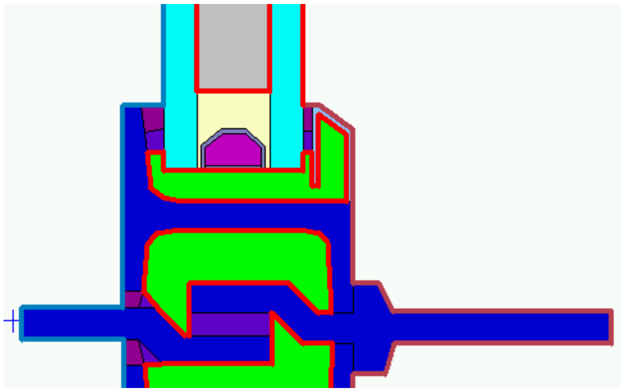

Fig. 7: Thermal modeling of repair option A4.

A4. New commercially available steel-frame window by Manufacturer #2 does not contain thermal breaks. Steel cannot easily be rolled or milled to form flared dadoes that can receive rubber, as in the aluminum components shown below in A6. As a result, the frame shows a low condensation resistance. The thermal break in the mullion is achieved in a way that would require specialized machining of the steel. Glazing is two panes 0.225” thick with ½” spacer containing desiccant. A low-e coating is applied to the interior of the exterior pane. A metal clip is seen at the right. The glazing is held at the left with foam backer plus sealant. Overall CR: 17.

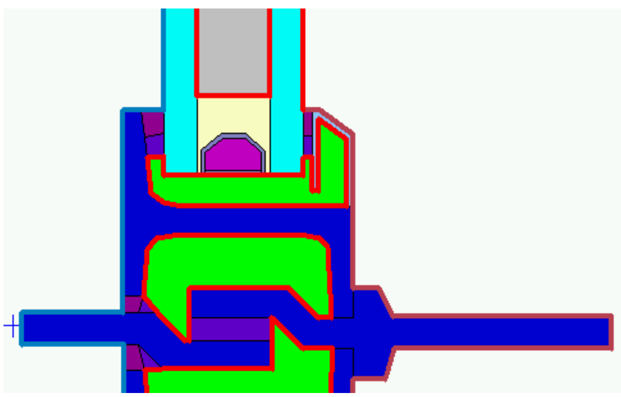

Fig. 8: Thermal modeling of repair option A5.

A5. New commercial steel-frame window by Manufacturer #1 is similar to window by Manufacturer #2. Glazing is the same. Mullion has a thermal break. Overall CR: 18.

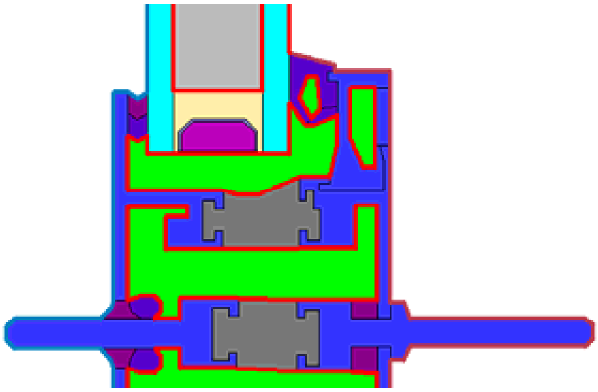

Fig. 9: Thermal modeling of repair option A6.

A6. New aluminum elements designed to have a profile similar to the original steel windows. This design was presented as part of the 1992 effort. There is a rubber thermal break element held in place by slots in the aluminum. It is likely that the extrusions for this design would have to be custom-prepared. Glazing is insulated glass unit with two panes 0.225” with a ¾” space. Overall CR: 43. This unit shows excellent condensation resistance.

A8: Exterior Treatment

A8. This trial leaves the original steel-frame intact. The glazing cavity that receives the single pane in the existing case would receive the innermost of the two panes in as shown in A8. This would require a special design of the IG pane, with one pane extending beyond remainder of the unit for mounting. The disadvantage here is that a greater thickness of the frame is opaque, and some of the glazed vision area is lost. The exterior material is stainless steel plate that can be easily (at some cost) milled to suit. Installation is secure because the glazing unit is installed only from the inside. Overall CR: 49. The Condensation resistance performance is acceptable.

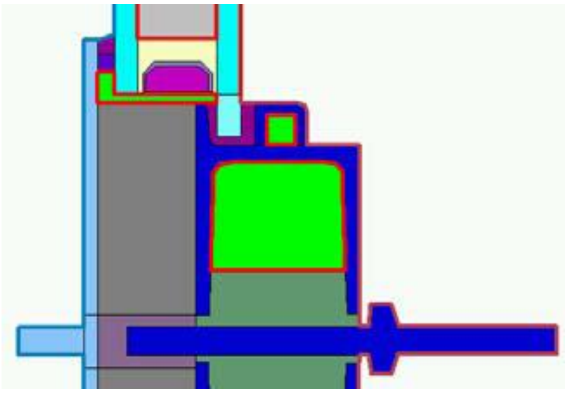

Fig. 10: Thermal modeling of repair option A8.

A9, A9a, A9b, A10: Interior Treatment

A9. A two piece aluminum assembly is fastened to the original steel assembly. Two layers of 1/16” insulating sheet (pyrogel) provide a thermal break between the steel and the aluminum.

The mullion is left intact. Glazing for A9 is insulated glazing with ½” air space. Overall CR for A9 is 25, due to the lack of a thermal break at the mullion.

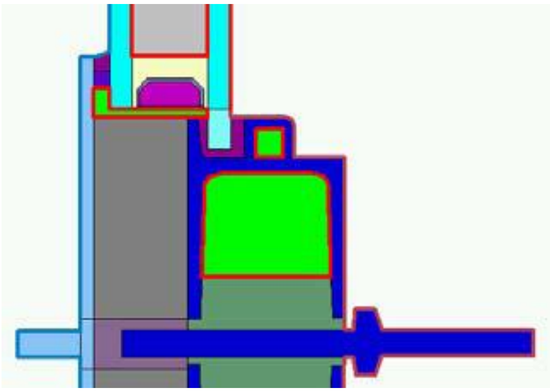

Fig. 11: Thermal modeling of repair option A9.

A9a. Same as A9, except the mullion is covered at the interior with insulating sheet (pyrogel) and an aluminum cap. This provides sufficient condensation resistance, lifting the unsatisfactory performance of A9 up to Overall CR of 41, which is very satisfactory.

A9b. Same as A9, except thermal resistance at the mullion is provided by a coating of 0.9 W/mK coating material at 1/16” thickness. The result is marginal performance—Overall CR of 33. This strategy had potential for being pursued further, by investigating other coatings or other thicknesses of coatings. Nevertheless, it should be noted that, to date, the improvement in performance does not meet the target value of 35.

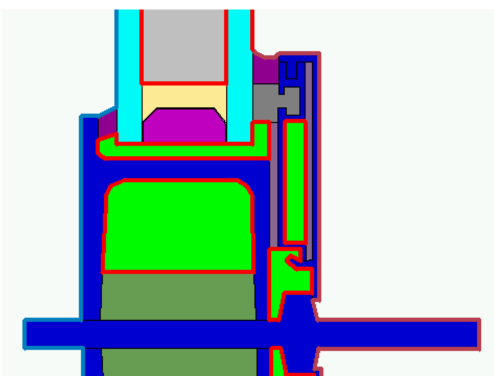

Fig. 12: Thermal modeling of repair option A10.

A10. Same as A9, except with IG units with a ¾” air space. This larger air space leads to slightly poorer performance, attributed, it is presumed, to the possibility of convection in the ¾” air space in large panes. Overall CR of 24-unacceptable.

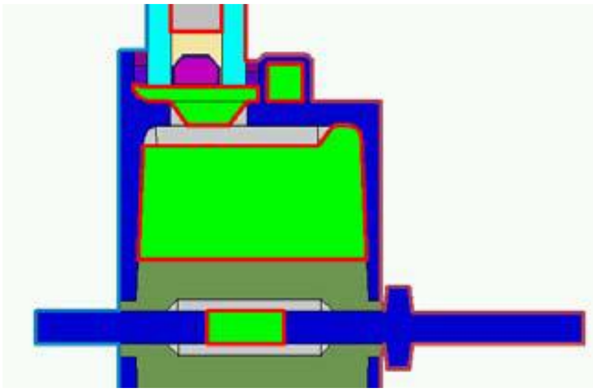

Fig. 13: Thermal modeling of repair option A12.

A12. In this option, the frame members are split apart (by removal and sawing), then reassembled with a space sufficient to accommodate the new IG unit. The interior and exterior aspect of the unit is exactly the same as the original. Resulting Overall CR: 38-acceptable.

Other options were studied. A summary of the CR values determined for all the options considered is presented in Table 3 below.

Assessment

This part of the study was aimed at providing an assessment of the condensation resistance of the various options under study. The following options were considered satisfactory: A6, A8, A9b and A12. Selecting an approach requires study of many other parameters. The preservation guidance set forth by WASA/Studio A offered several appropriate criteria. Table 4 presents some of those, together with other possible parameters for consideration. The evaluations given in Table 4 are subjective assessments by the authors. They are presented as a means to facilitate assessment by the designers and others, and not as a basis for decision-making within this document itself.

Table 3: Summary of CR values for all options.

		OPTIONS		**CONDENSATION RESISTANCE**							
		#	**CR Factors**	**Overall CR**	**CR @ Glass**	**CR @ Edge**	**CR @ Frame**	**Overall U-Factor**	**U-Factor @ Glass**	**U-Factor @ Edge**	**U-Factor @ Frame**
EXISTING	**3rd Fl.**	**A0.1**	Existing Glazed Enclosure at 3rd Floor Thannhauser	13.00	12	12	16	1.08	1.04	1.01	1.82
EXISTING	**4th Fl**	**A0.2**	Existing Glazed Enclosure at	13.00	12	12	15	1.08	1.04	0.81	2.6

			4th Floor Thannhauser								
REPAIR	Exterior	**A1.1**	New Exterior Insulating Steel Cover	22.00	69	48	22	0.424	0.255	0.364	1.18
		A1.2	New Exterior Insulating System	35.00	64	49	35	0.476	0.319	0.386	1.145
	Interior	**A1.3**	New Interior Insulating Steel Cover	43.00	70	49	43	0.401	0.255	0.347	1.023
		A1.4	New Snap-on Interior Insulated Metal Cladding with 1-1/4" IG Unit	24.00	49	36	24	0.618	0.46	0.521	1.356
		A1.5	New Snap-on Interior Insulated Metal Cladding with 1" IG Unit	26.00	69	45	26	0.463	0.255	0.353	1.417
		A1.6	New 1" IG Unit and New Steel Glazing Bead	16.00	100	31	14.7	0.46	0.26	0.62	1.35
		A1.7	New 1" IG Unit and Grey Gasket	19.00	69	46	19	0.45	0.255	0.367	1.27
		A1.8	New 5/8" IG Unit and Thermal Blanket	23.00	49	23	29	0.602	0.458	0.612	1.265
		A1.9	New 5/8" IG Unit and Existing Glazing Bead	17.00	50	37	17	0.618	0.441	0.492	1.44
		A1.10	Repair Existing Windows	13.00	12	12	16	1.08	1.04	1.01	1.82
REPLACEMENT	Al.	**A2.1**	New Custom-Made Thermally Broken Aluminum System	43.00	48	43	45	0.488	0.46	0.499	0.63
	Steel	**A2.2**	New Custom-Made Thermally Broken Steel System	36.00	69	52	36	0.362	0.255	0.335	0.773
		A2.3	New Steel Frame System by Manufacturer #1	19.00	69	44	19	0.43	0.255	0.374	1.51
		A2.4	New Steel Frame System by Manufacturer #2	17.00	49	37	17	0.574	0.457	0.525	1.47

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

Table 4: Response to Criteria (author's subjective estimate)

Conclusions

Four approaches to modifications of the Thannhauser Glazing were studied, including new systems, systems with modifications to the interior, those with modifications to the exterior, and those that involved splitting and bridging the existing units.

New systems must be either of readily-available steel or custom-made aluminum. New steel systems (A4 and A5) may capture 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) has good CR performance and the necessary extrusions would require custom manufacture, which is expected for a project of such significance. The main objection to this approach, however, derives from the performance of similar non-thermally broken aluminum –frame replacement units installed during the 1992 work. Field evidence indicates that these replacement aluminum units, which match the sightlines of the original steel-frame assemblies, exhibited buckling and misalignment, possibly as a result of undersizing.

Exterior modifications are possible (A8) and are likely to be effective; however the overall glass opening is slightly reduced, the sightlines are increased, and sourcing of the necessary glass and steel elements remains to be researched.

Modifications to the interior are promising, provided the mullion has some sort of thermal break (A9a). Interior cover designs 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, leaves the interior and exterior in practically the same state as the original while incorporating IG units; however the handwork may be laborious and the resulting product untested.

Recommendations

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

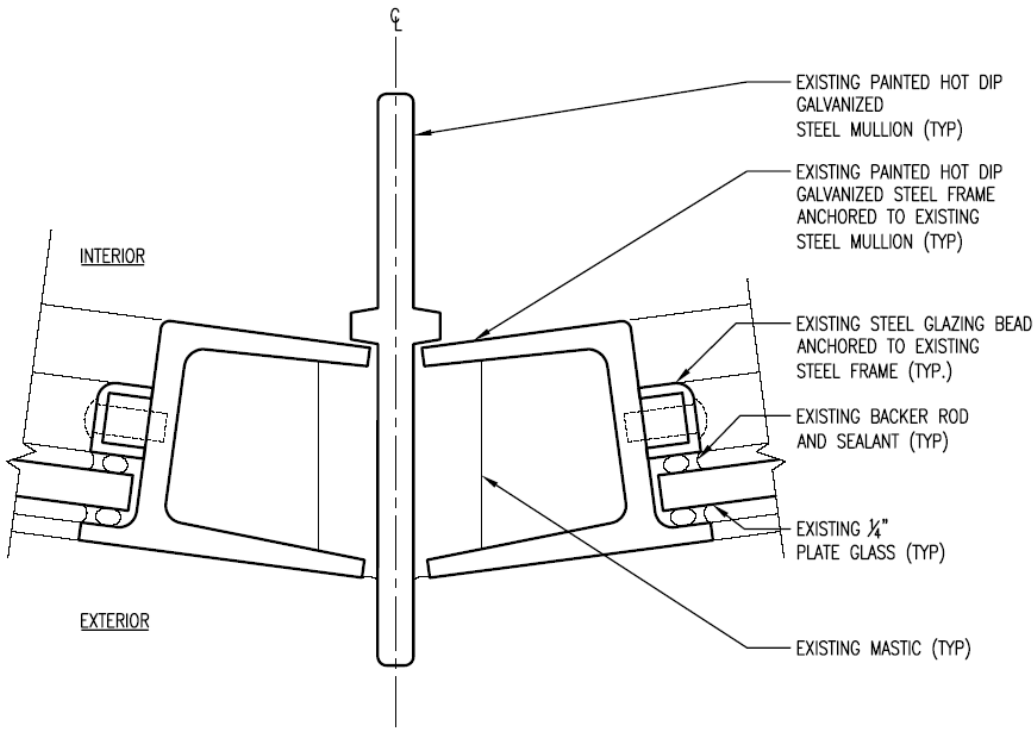

Fig. 14: Existing non-thermally-broken steel-frame system. Typical jamb detail.
Despite the good physical condition of the steel-frame glass walls, its poor performance made replacement the more appropriate upgrade option. For the Guggenheim glass-walls, enabling the year-long visibility implicit in the original design intent, and upgrading the environmental performance of this glazed enclosure according to contemporary museum standards, took precedent over the retention of original historic fabric in good physical condition.

As a result, an unprecedented thermally-broken steel-frame system, matching the appearance and sightlines of the original glass-wall, was fabricated and installed, according to a unique design by WASA/Studio A and William B Rose & Associates (fig. 15).

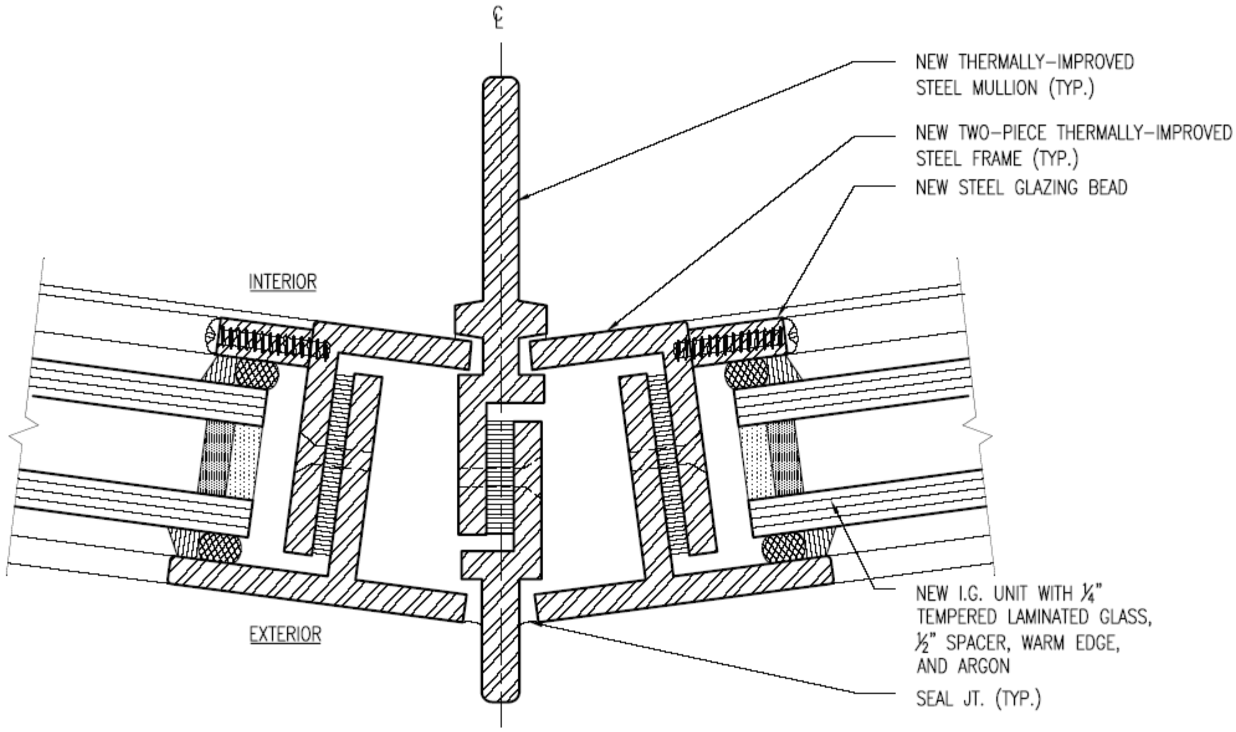

Fig. 15: Proposed thermally-broken steel-frame system. Typical jamb detail.

Laboratory Testing

Innovative construction details were proposed by selected manufacturers (fig. 16 and 17) to build the unprecedented system designed by WASA/Studio A and William B Rose & Associates. Two of these manufacturers were retained by the Guggenheim to construct equally-dimensioned mockups representative of the system proposed by each manufacturer. The mockups were designed to include configurations and details matching the existing conditions (fig. 18 to 20).

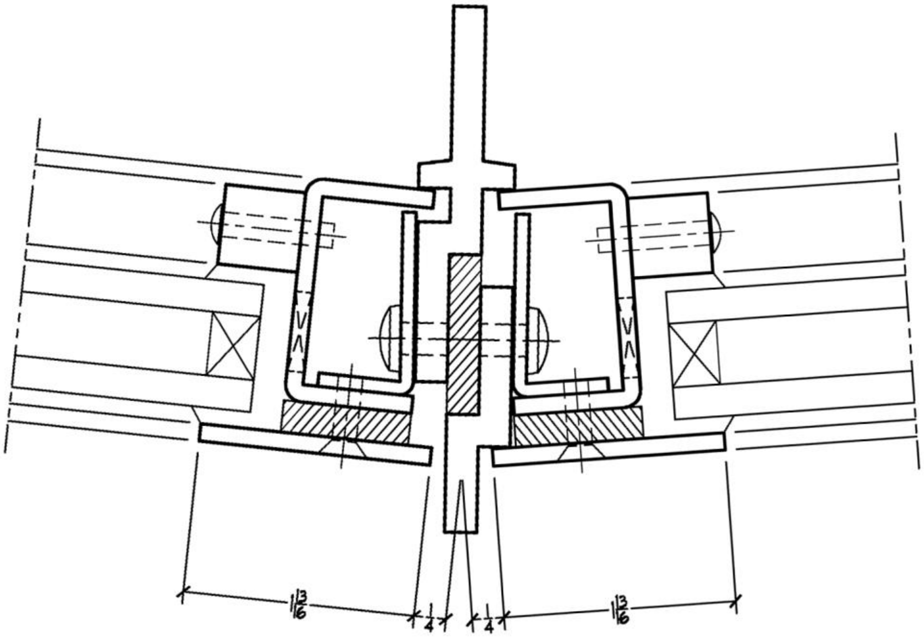

Fig. 16: Proposed thermally-broken steel-frame system by Manufacturer #1. Typical jamb detail.

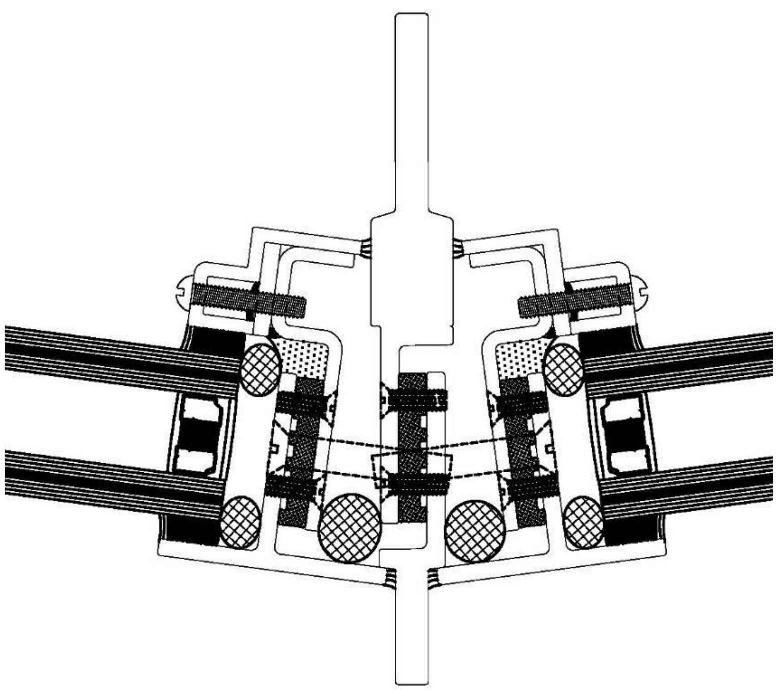

Fig. 17: Proposed thermally-broken steel-frame system by Manufacturer #3. Typical jamb detail.

The mockups were subject to a 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. Structural properties were tested per ASTM E 330 Standard Test Method for Structural

Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference. 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. The testing findings can be summarized as follows:

Fig. 18: View of typical mockup at testing laboratory.

Fig. 19 and 20: Details of existing onsite frame detail (left) and at testing mockup (right).

Fig. 20: Laboratory chamber where specimens were subjected to thermal testing.

Test Method	Test Pressure	Manufacture #1	Manufacture #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 in. Deflection Positive Load 0.092 in. Deflection Negative Load	0.010 in. Deflection Positive Load 0.018 in. Deflection Negative Load
U-Value	Btu/hr ft^2 °F	0.51	0.53
CR Factor	N/A	58	65

Table 5: Summary of comparative window testing of specimens by manufacturers #1 and #3. Note: CR Factor estimates were prepared by the manufacturer.

The testing results, along with a visual assessment of each specimen, allowed a more accurate assessment of each system's performance and appearance.

Scope of Work

Following the selected replacement approach, a set of construction documents were prepared, including drawings and specifications for window replacement. The documents outlined the extent of the removal and replacement work, as well as the performance requirements to be followed by contractors during the design, manufacturing, testing, transporting, erection, glazing and finishing of the new work.

The replacement work involved the removal of all the existing steel and aluminum windows and doors and the installation of a custom-made thermally-improved steel-frame system matching the appearance of the existing glazing. In addition to improved energy performance, the new glazing afforded enhanced light-transmittance reduction, sound and UV protection within a range more suitable to the museum environment. The interior and exterior appearance of the proposed system was designed to match that of the existing as much as permitted by the installation of the new insulated glass units, yet without any significant change to sightlines and general appearance.

Representative samples of the original steel-frame enclosure were retained as part of the museum collection to ensure archival preservation of such distinctive original historic feature.

The Architect provided part-time construction administration services for the window replacement work, including 1) Coordination with manufacturers to evaluate designated design of proposed thermally-broken steel-frame window system; 2) Review of shop drawings submitted by the window manufacturers for comparative testing; 3) Attendance to air- and water-infiltration testing, structural and forced entry testing of specimens by two selected manufacturers during comparative testing to select the window manufacturer; and 4) Review of shop drawings and samples submitted by the window manufacturer for window replacement.

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. In addition, the presentation will argue that when upgrade of historic glazed building-envelope systems is required, preservation mandates for in-kind material replacement must be pursued, along with an upgrade of system performance and retention of the original appearance and design intent.

References

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

[2] Vogel, Carol "Not Heat, But Humidity", *The New York Times*, January 14, 1994

[3] Ayón, Angel, et. al. "Preserving a Modern Icon: Recent Work at the Guggenheim Museum" Docomomo_US Newsletter, Spring (2009): 9-11.