Louis Kahn’s Stainless Steel Glazing System: Performance Upgrades in the Richards Building

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ABSTRACT

The Alfred Newton Richards Medical Research Laboratory (Richards Building) at the University of Pennsylvania is one of the most important buildings in the career of architect Louis I. Kahn and one of the great buildings of the 20th century (Figs.1 & 2). Designed 1957-1958 and completed in 1961 the Richards Building was at the time deemed an architectural milestone worthy of a solo exhibition at the Museum of Modern Art in New York. In 2008 the Richards Building was nominated for and granted status as a National Historic Landmark (NHL). As an NHL it must be treated with exceptional care, but as an occupied, working building it must with equal vigor and discipline consider necessary changes to its interior and exterior to better serve its functional purpose and the needs of present-day occupancy and operations.

A comprehensive renovation project was the catalyst for evaluating the exterior envelope and developing a design approach that retained the iconic visual and material characteristics of the building while radically improving the energy performance and functional qualities of the building. This presentation will review the history and development of Kahn’s glazing system, showing the comprehensive approach that was undertaken by an integrated design team to conserve the original steel framing while optimizing the overall performance of the exterior envelope and building systems. In this we sought to reconcile Penn’s very aggressive sustainability mandate with the exacting visual and material demands of working with a National Historic Landmark. Our process developed an optimal solution through sympathetic, evolutionary upgrades that balanced the demands of preservation and high performance design. In particular we will examine the process undertaken to select the right glass to replace the original polished plate units – and how to successfully glaze the new lites into the existing frames – that ultimately best balanced preservation, energy efficiency, economy and constructability.

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Figures 1 & 2 Historic photos of Richards Lab. Credit: University of Pennsylvanian Architectural Archives

INTRODUCTION

The 1950s was a period characterized by intense debate concerning the architectural expression of industrial production and even its elevation to high-art. The idea of foregrounding cutting-edge processes as primary representation is especially evident in the work of Louis Kahn, who believed in the "honest" expression of materials both in themselves and as components of a larger whole. Understanding and conserving this quality – which often relies on minimal, precise detailing, is an essential component in working with Kahn's architecture. As these building components and assemblies reach the end of their service life, architects today are presented with an opportunity to apply 21st century thinking and technology to the preservation and restoration of these important structures. At the same time, recognizing that environmental stewardship was not part of the equation that drove architectural production at in this period, reconciling Kahn's vision with contemporary standards of high performance design becomes a unique challenge. The Richards Building at the University of Pennsylvania (Penn) , a technically flawed but an internationally significant work of modern architecture, became an ideal candidate to test optimal strategies to address serious envelope and system performance issues. Its success, and that of projects like it will, we hope, serves as models for future performance upgrades of historically significant buildings.

Richards is comprised of a central "servant" brick tower that houses the primary service and circulation spaces. The core is flanked on the North, East, and West sides by the glazed "served" volumes housing individual laboratories. Exposed concrete Vierendeel trusses act as the primary structure with spandrel brick and CMU cavity knee walls. One of the signature elements of the Richards Building is the remarkable flush detailing of the exterior envelope which consists of co-planar exposed Vierendeel concrete truss structure, brick, and monolithic glazing set in bent stainless steel frames. Kahn's use of heavy gauge, matte finish sheet stainless steel, both as panel and brake-formed as a framing material became a trademark, though little discussed, element of his design vocabulary until the end of his career.

The use of this material arises out of Kahn's dissatisfaction with the options available in 1950s metal glazing systems. He used conventional steel rolled sections at the Yale Art Gallery of 1953, but was never happy with the heaviness and lack of precision in this system. He found aluminum extrusions "false" in their expression – and needlessly heavy in appearance as well. This led Kahn to develop the simple, minimal and very elegant brake-formed stainless steel system with which he was to work for the balance of his career. His quest begins with the American

Federation of Labor Medical Services building in Philadelphia (demolished 1973) designed 1954-55, where we witness Kahn's testing early details utilizing more conventional metal glazing sections before finally arriving at the stainless plate design. The system employed In Richards evolves out of these early explorations into one that uses the formed steel to create both shadows and strength, enabling a frame of unique lightness and incredible elegance (Fig. 3). Our presentation will focus in particular on the renewal of the most iconic glazing in the building, the monumental lights that form the corners of the served laboratory towers.

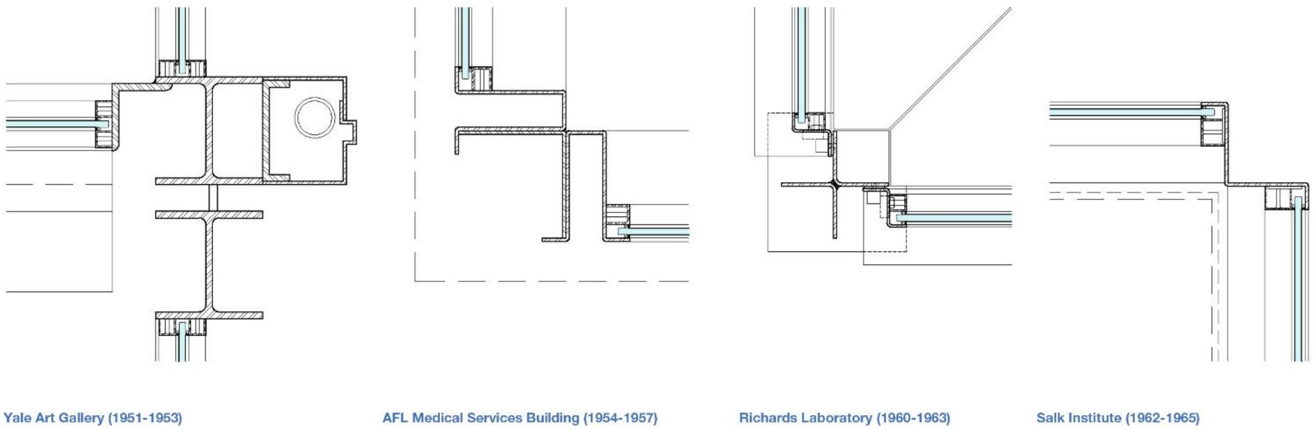


Figure 3 Kahn's development of steel framing details during the 1950's -60's.

It is important to understand this work in the context of the programmatic and performance goals set out by Penn for this project. Dysfunctional from a program standpoint, a decision was made early in the renewal process to change from a wet-lab use to dry lab, computational based science, in this particular instance a Center for Cognitive Neuroscience. This lightened the HVAC loads and enabled the adoption of a design strategy that could open up the laboratory floors to accommodate Kahn's vision to a degree that had not been possible since the building opened. Environmentally, Penn is committed to being as aggressive as possible in increasing the energy performance and sustainability performance of its existing building stock, so it was incumbent upon the project team to demonstrate that every reasonable measure was explored to enable an "energy frugal" structure. This all had to be balanced against Richards' status as a National Historic Landmark (NHL), which places severe restrictions upon changes to the building's exterior.

METHOD

Approaching the project in situ, rather than during the design process, presented the challenge of thinking forensically from the outset. Beginning with site probes and analysis of existing conditions, the team worked through mock-ups and rigorous testing to establish as precisely as possible baseline performance metrics against which the effectiveness of the proposed interventions could be measured.

The University of Pennsylvania sets ambitious performance benchmarks for campus buildings. Because of this policy, the team had to take very seriously the option of removing the entire glazed assembly and replacing it with new thermally broken frames and insulated glazing units (IGU). Numerous stainless steel window manufacturers were consulted to establish fabrication limitations for formed stainless steel frames and the integration of thermal breaks. Using these limitations, options were developed and coordinated with the mechanical engineer to provide improvement metrics scaled from the lightest touch (in-kind replacement) to the most dramatic intervention (full system replacement) (Fig.4). Taking all of the options under consideration, it was determined that the optimal solution would be to focus on improving glass performance and restore the existing frames. This made sense because the existing frames were in very good condition and the glazing makes up the largest percentage of the total area under remediation, thereby allowing the greatest possible performance gains with the least risk to historic character. Replacing them would have essentially meant scrapping perfectly serviceable stainless steel and replacing it with stainless steel of marginally improved energy performance, as well as risking considerable damage to the concrete and masonry surrounding the frames in the course of removal.

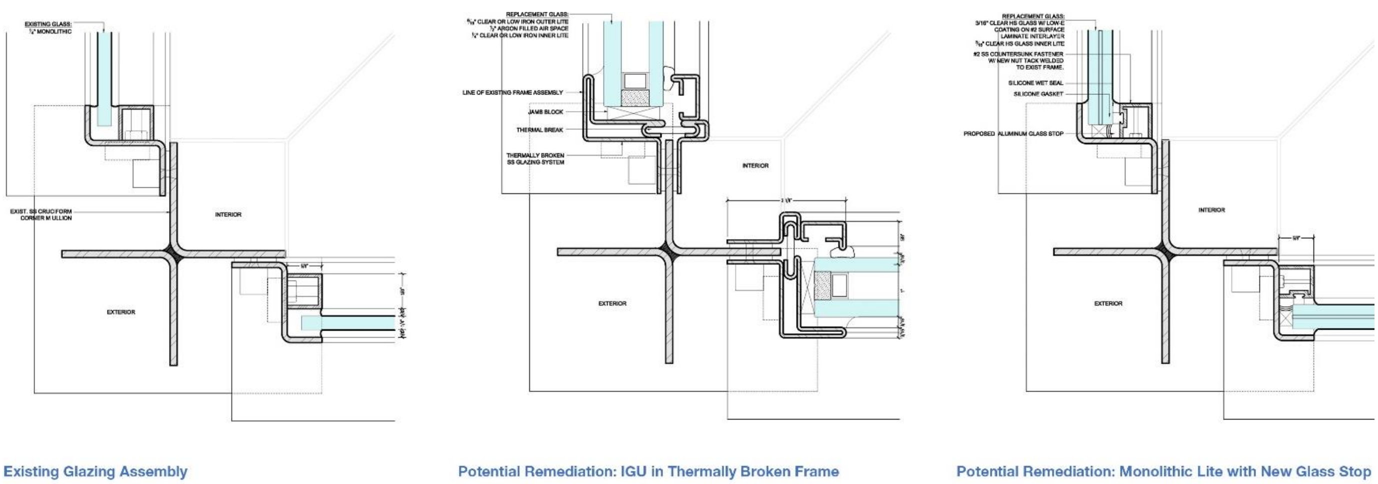


Figure 4 Comparison of existing and potential frame remediation options. Note the profile change required to allow for thermally broken frames.

One important caveat is that using the existing frames meant that IGU's were precluded due to the frames' shallow profile relative to the IGU depth; the IGU would project farther than the innermost face of the existing frame. Acknowledging performance improvements as secondary to historic restoration and sustainability, the decision was made to keep the existing frames. Replacing the monolithic glass with IGU's and replacing the frames with new members of different thickness and sight lines would have been tantamount to installing a system installing a system designed by another architect.

Vision Glass: Investigation and Analysis. The corner labs are comprised of three main glass types: Corner Vision Glass (W-1), and Clerestory Glass (W-2 and W-3). (Fig. 5). Conformance with the original specification of ¼" (6mm) plate glass was confirmed through field measurements and observation of telltale "score-and-snap" edge work concealed behind the glazing bead. Comparison of historical strength characteristics of polished plate glass suggests parity with contemporary annealed float glass. Therefore, annealed glass characteristics were used for analysis of glass stress and deflection. Wind loads calculated in conformance with ASCE 7 and based on a 50-year wind event reflect positive and negative pressures of +20 psf (9.6 x 10-4 N/mm2) and -35 psf (1.68 x 10-3 N/mm2) respectively. Under these loads, ¼" (6mm) thick annealed or polished plate glass would be overstressed. However, because a large number of the original lites had been observed intact, the 50-year wind event may not have been experienced yet and the replaced lites may represent statistical breakage pattern at a lower pressure. A comprehensive record of historical glass breakage was not available, but anecdotal evidence shows reports of periodic breakage during extreme weather events, the most recent of which was Hurricane Irene in 2011. Where replacement glass was visible, two narrower lites had been installed by adding an intermediate vertical mullion- this deviated from Kahn's original intent.

From a performance standpoint, the original glass was uncoated and provided little thermal benefit.

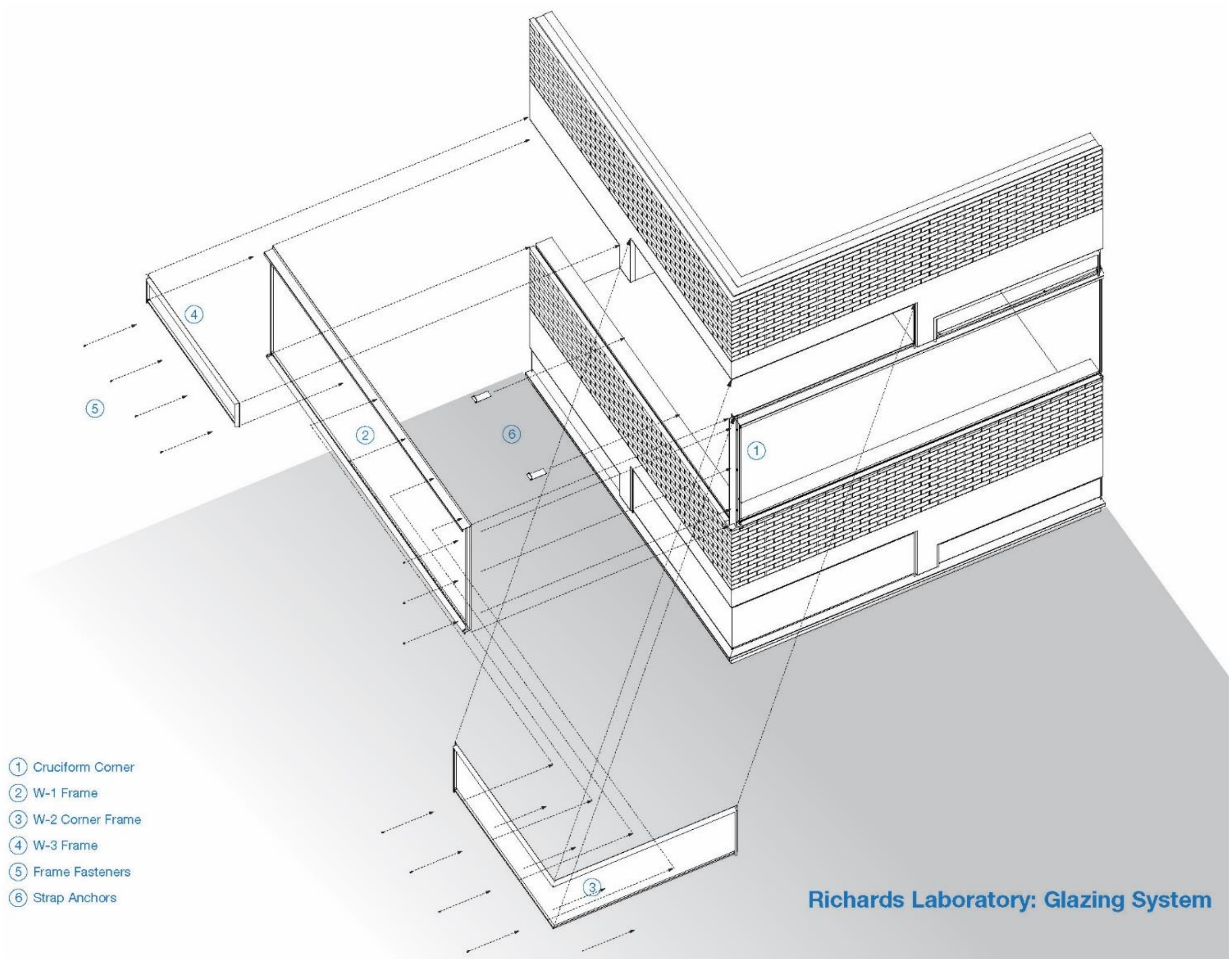


Figure 5 Exploded diagram showing the three main glass types and their assembly methodology.

Vision Glass: Remediation. The original monolithic glass was replaced with a laminated lite of twice the nominal thickness. The replacement glass addresses concerns of the glass being overstressed in a wind event. Various treatments to optimize the potential performance of the replacement glazing were considered:

Option V1: High-performance low-E coating on the #2 or #3 surface of the laminated replacement lite.
Option V2: High-performance pyrolytic low-E coating on the #4 surface of the laminated replacement lite.
Option V3: High-performance XIR film integrated into the PVB interlayer of the laminated replacement lite.

Full size mock-ups were constructed on-site (Figs. 6&7) and reviewed by the design team and the University to ensure that the character of the original glazing was maintained. The low-E coatings were favorable due to their neutrality and the minimal workmanship concerns – the inclusion of an XIR film in the laminate exhibited the tendency to "orange peel" during production, and the elimination of this effect could not be guaranteed by the manufacturer. Comparing color neutrality with the existing uncoated glass was also of particular importance. Ultimately, the first option (V1) was selected, utilizing coated heat strengthened substrates of both clear and low iron composition:

W-1 Replacement Glass
¼" (6mm) Clear Heat Strengthened Glass with VE-85 coating on the #2 Surface
0.060" (1.5mm) Clear Polyvinyl butyral (PVB) interlayer
¼" (6mm) Low Iron Heat Strengthened Glass

Figures 6 & 7 Visual Mock-up for review of replacement glass options; selected options installed on in-situ mock-up.

Clerestory Glass: Investigation and Analysis. The clerestory glass set above the W-1 units consist of two types (W-2 & W-3) and two finishes based on location. Clear vision glass was installed at all locations on the North elevation. On the South, East, and West elevations, Kahn used a textured, blue-tinted, cast glass ostensibly to cut down on solar heat gain and address user comfort. Though a canny design decision, in the absence of the fixed external shades originally designed, the glass alone did not provide enough solar heat reduction. Over the years, the users responded by applying various foils and films in an effort to keep the labs from overheating (Fig. 8).

Figure 8 Over time, laboratory users applied various foils and shades to minimize solar heat gain.

Physically, the clerestory glass-to-glass corners were in poor shape. Originally sealed with calcium carbonate glazing putty, the seals had deteriorated under exposure and were stressed in shear by the diverging movement of the glass caused by creep of the concrete structure. The movement of the structure also worked in tandem with the hyrgic expansion of the brick veneer to push the base of the cruciform corner outwards as much as ¼”. Restrained at the head by the welded clerestory frame, a slight rotation force was induced in these locations, leaving many unsealed or in extreme cases, cracked.

Clerestory Glass: Remediation. In-kind replacement was not an option; the original manufacturer had gone out of business and suppliers of similar patterns could not provide custom colors. Samples and mock-ups were reviewed with different glazing options:

- Option S1: Laminated lite comprised of a clear Pattern 62 outer ply, blue interlayer, and a clear inner ply.
- Option S2: Laminated lite comprised of a clear Pattern 62 outer ply, clear interlayer, and a body-tinted inner ply.

Complicating the matter was the specification of laminating interlayers in these glass-to-glass corner locations. Polyvinyl Butyral (PVB) is a hydroscopic material that may absorb atmospheric moisture over time. This absorption of moisture causes a temporary cosmetic edge delamination, clouding, or "blushing" on the glass 1/4"-3/8" (6mm-10mm) from the edge. None of these effects are critical to the structural integrity of the glass, but are visual anomalies that the team wanted to minimize.

Ionoplast interlayers were therefore specified because their chemical formulation is fundamentally different than PVB and is not prone to blushing or delamination. However, adhesion of ionoplast is dependent on knowing which side of the patterned glass was in contact with the molten tin (i.e. “tin-side”) when coming off the float line. The potential glass suppliers could not guarantee consistent results. To counter this, adhesion promoters are sometimes but less frequently used due to their caustic environmental impacts. The decision was made to use the PVB interlayer despite the blushing concern, anticipating any visual impacts would be distorted or obfuscated by the pattern of the textured glass:

W-2, W-3 Textured/Tinted Replacement Glass
3/16” (5mm) Clear Pattern 62
0.060” (1.5mm) Clear Polyvinyl butyral (PVB) interlayer
1/4” (6mm) Arctic Blue Heat Strengthened Glass

For the clerestory vision areas, there would be no distortions of the textured glass to obscure any cosmetic effects. Matching the W-1 glass types was also problematic because the exposed PVB might lead to corrosion of the low-E coating. The final resolution was to omit the interlayer and coating entirely in these small areas and provide:

W-2, W-3 Vision Replacement Glass
½” (12mm) Clear Fully Tempered Glass

Tempering was used to accommodate the ground level locations where safety glazing was required. The visual difference between the coated laminated W-1 glass and the uncoated W-2/W-3 glass was negligible.

Seals and Accessories: Investigation and Analysis. The specification for the original glazing putty stipulated "Elastic Glazing compound Federal Spec TT-P-781a, Type 1. Probes were conducted to remove representative samples of existing glazing putty and fibrous backer materials for asbestos abatement testing. The materials tested negatively for asbestos, but had either cracked, reacted negatively with remedial over-seals, or deteriorated completely leaving large holes in the primary air seal of the façade system.

Other gaps in the air seal were present between joints in the welded unit frames allowing air and moisture to migrate through the frames at the perimeter of the glass. At the interior, extruded aluminum glass stops were held in place by a carbon steel threaded receiver welded to the frame and secured into the receiver with stainless steel fasteners. Whether by condensation, water infiltration, or both, the carbon steel receivers were found to be uniformly corroded and in need of removal or replacement. (Fig. 9)

Figure 9 Condition of existing frame assemblies and materials; corroded glazing bead receiver, metal shim, and gap in metal-to-metal frame connections.

Seals and Accessories: Remediation. Coupled with the poor condition of the original components, increasing the thickness of the glass necessitated a reconsideration of the glass stop attachment strategy:

- Option GS1: Two-part extruded aluminum glass stop with snap attachments. Mock screw heads installed in the snap trim to mimic the existing condition.
- Option GS2: Single aluminum extrusion structurally silicone glazed to the replacement glass and affixed with "Very High Bond" (VHB) tape to the existing frame.

Reviewing the options, it was apparent that a mechanical attachment was no longer possible without encroaching on the character and appearance of the original frame. Furthermore, the extremely small dimensions of the area (approximately 5/8" (16mm) x 7/8" (22mm)) would make installing a two-part stop with any level of precision a difficult if not impossible process. Option GS2 was selected with the qualification that structural testing be included as a "proof-of-concept" that the silicone and VHB tape could adequately support the glass under wind loads.

Addressing the existing issues with air and water infiltration, a heel bead of sealant was provided to act as the primary air seal at the perimeter of the laminated replacement glass. The existing inconsistencies in the frame welds allow a measure of protection from liquid water and pressure-equalize the glazing cavity to the exterior. Finally, the gaps between the connections of individual unit frames were sealed with clear narrow joint sealant to provide continuity with minimal aesthetic impact.

FAÇADE STRUCTURE

Framing: Investigation and Analysis. The framing is comprised of stainless steel sections welded into individual rectangular unit frames for each lite size. Each welded frame is fastened with regularly spaced stainless steel fasteners to the adjacent frame unit, and anchored between clerestories with a clip angle set into the downturned concrete truss. At the masonry jambs, one leg of the unit frame is fit into a reglet in the concrete with mastic at the exterior while at the interior face, a serrated aluminum angle is friction fit into the reglet in order to anchor the frame.

At the outside corner between large vision lites (W-1), two bent stainless steel plates are welded back-to-back to form a "cruciform mullion." Through-fasteners mechanically attach the frames to the cruciform mullion. This cruciform mullion is welded to a stainless steel stanchion base plate, which is grouted at the masonry sill. At the head, the cruciform mullion has been notched to allow the frame of the medium clerestory lite (W-2) to slot into it. At the outside corner of the medium clerestory lite (W-3), the unit frame is comprised of two (2) three-sided frames mitered and welded together resulting in a 3D unit, sealed glass-to-glass. Two stainless steel clips have also been applied at this corner, which are not shown in the original architectural drawings and were not consistently applied on site.

The large window unit frames (W-1) are grouted at the masonry sill and have stainless steel strap anchors connecting them to a CMU backup wall at the sill.

Using a self-leveling laser on top of the sill frame at the North and East elevations, head and sill frame conditions appeared to be level from the masonry jamb to roughly the mid-span of the large vision lite (W-1) then deflecting downward towards the outside corner. This downward deflection is consistent with expectations of the long-term structural creep of the Vierendeel truss members.

Framing: Remediation. Structurally, the existing stainless steel frame did not require additional reinforcement to support the dead load of the replacement glazing. However, computer analysis of the corner window (W-1) configuration at ASCE calculated wind loads show that without restraint at the sill, frame deflections would exceed four (4) inches during a significant wind event. As there is no evidence of this degree of movement, there are likely a combination of factors contributing to the frame support and stability including:

- the weight of the glass
- the adhesive properties of the grout bed
- the strap anchors.

The strap anchors were secured with carbon steel cut nails. In many locations these cut nails were found to be loosely fit or otherwise anchored into a deteriorated grouted cavity of the 4" (100mm) CMU backup wall, providing an inconsistent substrate for the fastener. To ensure structural suitability, the cut nails were removed and replaced with pre-engineered fasteners set in non-shrink grout.

The stainless steel material itself required minimal remediation. The frames appeared to be in serviceable condition despite no record of regular cleaning. Dirt accumulation and superficial pitting was consistent with what would be expected of a 60 year old building and the near-flush design of the façade facilitated by regular rain-washing. Remediation required a simple re-passivation in which the exogenous contaminants on the stainless steel are stripped with a nitric acid solution, allowing the chromium in the material to re-oxidize under exposure to the atmosphere and create a new protective layer of chromium oxide. Construction was coordinated so that this process was conducted between the removal of the existing glass and the installation of the replacement units to ensure all surfaces of the frames were addressed.

IMPROVING PERFORMANCE:

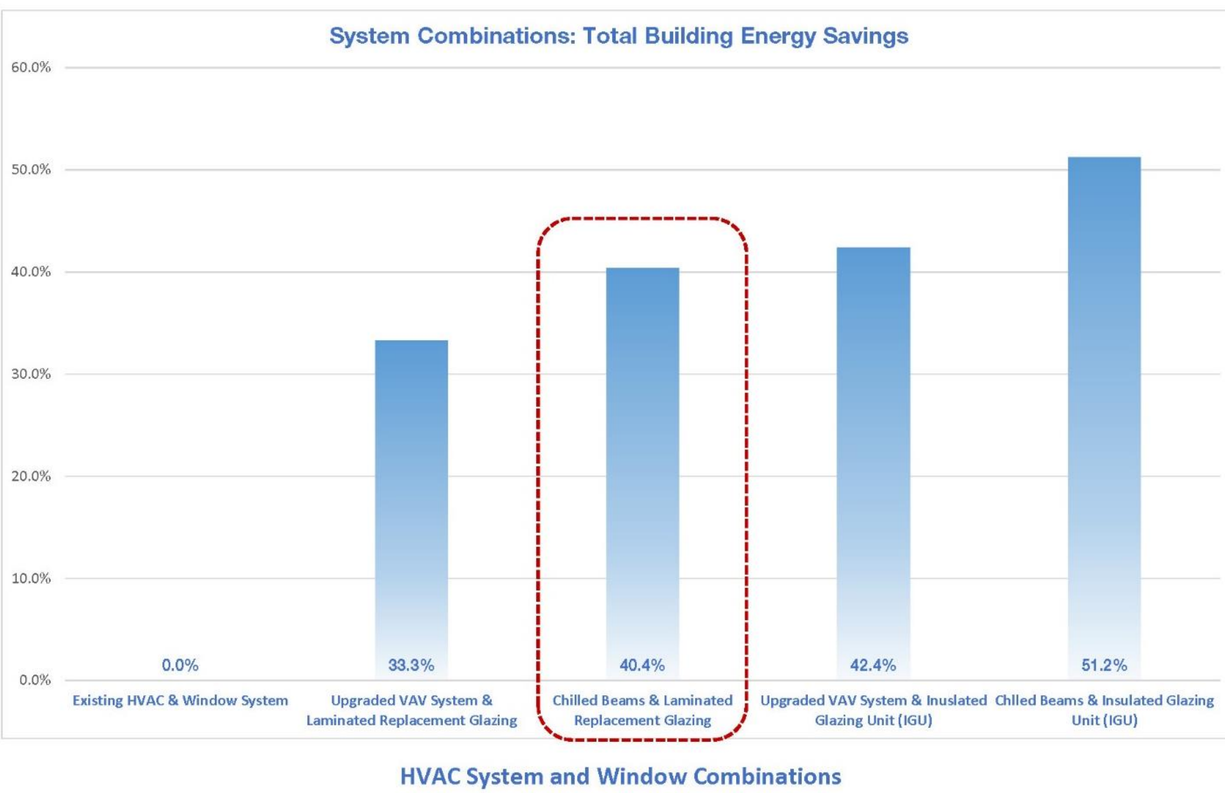
Thermal + Solar. To establish performance baseline targets, an in-house computer-simulated thermal analysis was conducted using the computer software developed by Lawrence Berkeley Laboratory, Therm 6.3 and Window 6.3. The computer program is recognized by the NFRC as accredited software for simulations. Simulations were conducted to determine the Solar Heat Gain Coefficient (SHGC) and average U-values to test the following assumptions:

- Improvements in SHGC will result in lower cooling loads.
- Improvements in U-values will result in lower energy use (primarily in the Winter) and better condensation resistance.
- In Philadelphia's climate, mechanical systems' energy use is dominated by cooling loads.

The biggest improvement with the laminated glass replacement option is in lower cooling loads reflecting the improvement in SHGC. Improvement in system U-value is limited when compared to the existing condition because the effective thermal transmission is not reduced to any appreciable degree without the addition of the air space attending use of an IGU. Comparisons were conducted for two domestically supplied coatings which could be fabricated against the interlayer of a laminated lite:

- VE-85
- VLE-70

As anticipated, there was parity between the system U-values for each coating. The SHGC of the VLE-70 coating was a 30% improvement over the VE-85, 0.60 vs 0.43 respectively, but was not selected due to the negative visual impact of this coating relative to the appearance of the original glass.



Note: *Laminated Replacement Glazing* reflects 3/8" minimum laminated glazing with VLE-70 Coating on the #2 Surface. *Insulated Glazing Unit* reflects a 5/16" outer lite with VE-2M on the #2 Surface, 1/2" Argon Space, and 1/4" inner lite.

Figure 10 Energy analysis comparing various glass and MEP remediation options.

The stainless steel frames are not thermally broken, so retaining them also meant accepting a higher risk of condensation. At the interior system surface, a dew point temperature of 32° F was determined using preliminary indoor air criteria of 70° F and 25% Relative Humidity. The exterior boundary condition was determined using the 99.6% Heating Dry Bulb and Mean Coincident Wind Speed design conditions for Philadelphia in 2005 ASHRAE Fundamentals. Based on these conditions, condensation would be limited to the stainless steel frame when the temperature drops below 25° F (-4°C). To address these concerns, the original perimeter radiant heating elements were replaced with more efficient and better-located units to increase the surface temperature and convection currents adjacent to the glazing. Taking the façade and MEP upgrades together, an overall energy savings of 40% was achieved when compared to the original existing conditions. (Fig. 10)

Air + Water Infiltration. A testing protocol was proposed to determine the air/water infiltration of the existing system; it was well-understood that there were obvious points of failure, but obtaining existing performance metrics aided in quantifying improvements of the remediated conditions. The tests conducted, in order, were:

- *ASTM E 783- Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors.*
    - To determine the air leakage rate, the leakage rate of the adjacent construction needed to be determined independent of the window system. To do this, the former was measured in isolation and subtracted from the latter by the following procedure:
    - A polyethylene plastic sheet, also noted as a "tare bag", was installed at the exterior of the assembly and sealed to the perimeter conditions with duct tape.
    - The chamber was pressurized to the specified test pressure of +/- 6.24 PSF, and the flow rate measured to determine the leakage rate not attributable to the windows, such as inconsistencies in the chamber construction, adjacent conditions, etc.
    - The tear bag was removed, the chamber was again pressurized to the specified test pressure of +/- 6.24 PSF, the flow rate was noted, and the first reading was subtracted from the second to determine the net air leakage rate of the existing windows.
        - Leakage Rate with Tare Bag: 41 CFM @ 6.24 PSF pressure difference.
        - Leakage Rate without Tare Bag: 76 CFM @ 6.24 PSF pressure difference.
        - Leakage Rate of Existing Assembly: 35 CFM @ 6.24 PSF pressure difference.
            - 204 SF (Frontage Area) x .09 CFM/SF of Frontage (Specified Allowable Air Leakage)
                - The specified value of .06 CFM/SF reflects a laboratory testing environment, whereas a modification factor of 1.5x is applied to field conditions per the test standard.
        - Allowable Infiltration: **18.36 CFM**
        - Actual Infiltration (Existing): **35 CFM**
        - Actual Infiltration (Remediated): **1 CFM**

The net effect on the overall air infiltration was clear. The inclusion of the heel bead in the glazing pocket and sealing of the metal-to-metal frame components provided a great improvement in overall air infiltration performance. The water infiltration, however was less conclusive.

- *ASTM E1105 – Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows,* *Skylights, Floors and Curtain Walls by Uniform Static Air Pressure Difference.*

- To pinpoint locations of water penetration in the existing windows using ASTM E 1105, a consistent volume of water was sprayed onto the exterior of the window system through a suspended hose rack while the test chamber is negatively pressurized to 10 PSF at the interior.

As expected, water infiltration during the initial test water came in so rapidly and at such volume that the test procedure was suspended immediately. The remedial testing of the window system was successful, but highlighted the porosity of the existing masonry, which was outside of the remediation scope. The glazing system had been so well sealed that the weaknesses and inconsistencies in the remaining assemblies were then cast in sharper relief. More broadly, it raises the theoretical question around the limits of subjecting 20th century construction to performance testing designed for contemporary 21st century construction.

CONCLUSION AND FUTURE WORK

The project addresses many of the issues that confront working with mid-century modern structures. Though balancing respect for its Landmark status as a signature work of Louis Kahn against solving acute functional performance issues made this an especially exacting project, our success should not be considered an anomaly for these types of projects (Figs. 11 & 12).

It is important to understand that this is a renovation of a working laboratory building, and that our charge was to accomplish at times radical internal change with virtually no exterior visual impact. While Richards is in many ways unique, it does speak to a more general necessity to balance conservation of original materials with performance enhancement. The interventions to achieve this replacement of key building elements is critical when it is necessary to ensure the continued viability of a building – and to carefully design, mock-up and test these components to ensure that they meet team expectations for both performance and appearance.

Perhaps therein lies its greatest assertion – significant improvements to building energy performance are possible without altering the historic character of a project. Its success underscores as well the significant mandate that historic structures, and indeed any existing building, share with new construction for improving energy performance in the 21st century. New construction alone cannot bear responsibility for reductions in total building energy use and the upgrading of a building as sensitive and important, as Richards is a particularly salient case study by which standards and methods of practice can be set to find optimal approaches for the rehabilitation of mid-century modern buildings. This process has thus far served the team well, but we are still and will always be learning.


Figure 11 View of Richards from College Walk. Remediated wing is foreground-right. Credit: Halkin Mason

Figure 12 View of remediated wing, looking at the laboratory spaces and connection to the service core. Credit: Jeff Goldberg, ESTO

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