Proceedings of the IASS 2022 Symposium affiliated with APCS 2022 conference
Innovation·Sustainability·Legacy
19 – 22 September 2022, Beijing, China

The Mitchell Park Horticultural Conservatory in Milwaukee, Wisconsin

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Abstract

The Mitchell Park Horticultural Conservatory consists in part, of three conoid structures, referred to as "The Domes". Each dome is 26 m tall and has a 43 m base diameter. The main structure for each dome is a precast concrete frame, supporting an aluminum framed wire glass cladding and a steel framed apex. The precast concrete frame is a series of hexagons, diamonds, and triangles which make up the conoid shape. The domes were designed between 1955 and 1962 through collaboration of engineer Charles Whitney (of "Whitney Stress block" fame in plastic analysis of concrete) and architect Donald Grieb. These domes were developed concurrently with other famous projects including collaborations with Eero Saarinen on early thin-shell concrete structures such as Kresge Auditorium (1955), TWA Flight Center (1962), and Dulles International Airport (1962). Construction of the Mitchell Park Horticultural Conservatory began in 1959 and proceeded in stages until 1967 with the opening of the arid-climate dome. After continued use over a life span of 60 years, without much maintenance being carried out, the Domes need extensive rehabilitation along with repairs and updates. Using historical documents and forensic site visits, this paper presents the history and the details of the design and construction, emphasizing the historic value of these unique structures.

Keywords: concrete grid-shells, historic structure, modular concrete, integrated design, glazing system, in-situ performance, conoid frame.

1. Introduction

1.1 Project Summary

The Mitchell Park Horticultural Conservatory complex consists of three large conoid shaped greenhouse structures, a central lobby area, and a transitional greenhouse as shown in Figures 1 and 2. Colloquially referred to as: "the Domes" these three structures are historic haecceities for several reasons: 1) they mark a distinct departure from standard greenhouse/horticultural building designs up to 1959 (resulting in two patents – one for the structure and one for the façade) 2) they are the only known conoidal space frame structure designed by both Whitney and Grieb and 3) they are an exceptional example of integrated design (structure, architectural, MEP and construction demands all weighed equally on the design) and 4) the design of the domes shows an important structural methodology that simplifies complicated analysis into an efficient and constructible design [1, 2]. Construction of the complex began in 1959 and proceeded in stages with the Show Dome opening in 1964, the Tropical Dome in 1966, and the Arid Dome in 1967. The architect of record was a local architect, Donald L. Grieb and the structural engineer of record was Charles S. Whitney, (consulting engineer). Grieb won the design competition for his glass dome entry and partnered with Super Sky Products Enterprises, LLC (Super Sky) as the designer and installer of the glass and aluminum structure that clads the domes. Construction engineering and project management of the domes was provided by John Hufschmidt, President of Hufschmidt Engineering. [3, 4]

Figure 1: The Domes (Credit Jamie Johnson, Milwaukee County Historical Society)

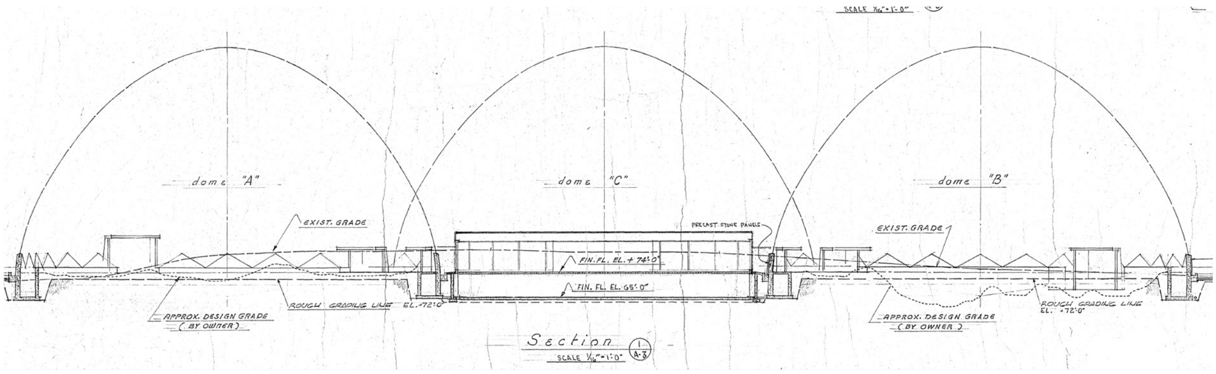

Figure 2: Conoidal Dome Cross-sections from Original Plan Set (Milwaukee County Historical Society)

Each dome was designed to house a distinct microclimate to exhibit a variety of plants in a natural ecosystem setting. The Show Dome is used for seasonally changing horticultural exhibits, while the microclimate and vegetation of the Tropical Dome and Arid Dome are kept the same as befits their namesake.

The domes are glass-and aluminum clad with a triangulated structural precast concrete frame to form a conoid-shape dome. The precast concrete members were fabricated onsite during construction and held to ±15.875 mm. The domes are supported on circular, reinforced concrete foundation walls. The glass and aluminum framework is connected to the precast concrete frame with stainless steel connection posts. The aluminum framing for the glazing system serves the dual purpose of supporting the ~10,000 individual glass lites as well as properly draining the anticipated condensation from vegetation.

Each dome has a height of 25.91 m and a base diameter of 42.67 m. Individual domes are supported by a structural precast concrete frame supporting an aluminum frame and glass infill. The façade consists of a novel integrated moisture condensation system within the aluminum frame. The concrete was formed on-site using a series of repetitive forms that allowed consistent and efficient construction of the structural modules as designed by Hufschmidt Engineering [3, 4]. Construction of the curved surface via precast concrete frame was achieved using a series of triangular, quadrilateral and hexagonal site-cast modular units used to tesselate the conoid shape over temporary shoring. Each of the domes has an oculus which is capped at the apex with a self-supporting steel structure (i.e., a "mini-dome") housing the mechanical, electrical and HVAC infrastructure for the domes [5-8].

1.2 Project Engineer: Charles Whitney

A significant reason for the historical importance of The Domes is that they are the only constructed space-frame project designed by Charles S. Whitney. A prolific and innovative engineer, Whitney was born in Pennsylvania in 1892, graduated from Cornell University in 1915 and established a consulting firm in Milwaukee, WI in 1919 which subsequently became part of Amman & Whitney in 1946.

Whitney is best known for his contributions to plastic theory (i.e., ultimate strength method) for reinforced concrete design [9, 10]. Most significantly, the eponymous Whitney Stress Block, has been a ubiquitous part of modern concrete design since its adoption by the American Concrete Institute (ACI) in 1956 [9]. Whitney heavily contributed to the ACI's Manual of Concrete Practice and even served as President of ACI in 1955. In addition to concrete design theory, Whitney has significant quantity of professional designs for bridge and long span shell structures [11-15]. His developments in concrete and construction (both theory and design) served a number of well-known clients including Eero Saarinen.

At the time of the design for The Domes, Whitney was 67 years old and had a wealth of concrete and construction knowledge that he used to support the development of the innovative space frame structure for The Domes. Notably, Whitney had developed a robust understanding of thin shelled concrete structures and principal stresses which were used in development of the layout of structural members for The Domes [4, 9, 14].

1.3 Project Architect: Donald Grieb

Donald Grieb (born 1918) was one of 33 architects being interviewed by representatives of Milwaukee County during the month of May 1957 to find a designer for a new greenhouse within Milwaukee's Mitchell Park. Most architects and architectural firms which came to the interviews could rely on an impressive body of work, and they tried to assure the board that they had a good understanding of the task. However, young architect Grieb did not have much of a list of references. Instead, he had a "sweeping energy and could convince the board of his ideas" [5]. Mr. Donald Grieb presented studies that he had prepared, some of which covered the "Jewel Box" at St. Louis, Missouri [5].

Figure 3: Architect Donald L. Grieb holds a piece of foam insulation he designed in his office on June 23, 1982. (Credit Paul F. Gero, Milwaukee County Historical Society)

In addition, he shared his design for the National Opera House of Sidney, Australia, in connection with the competition which he had entered, and which was sponsored by the Commonwealth of Sidney. While he was not the winner of the competition the winning solution did contain a similar design. Mr. Grieb explained his draft of a shell-like structure of concrete and mosaic finish. Because Mr. Grieb felt that there is pertinent material in his studies which could be very helpful to the commission, whether or not he is selected, he offered the studies to the Park Commission.

Among the illustrations presented by Mr. Grieb was a hyperbolic paraboloid structure of thin-shelled concrete, and this thin-shelled concrete method, he believed, will revolutionize industry by allowing construction of structures that heretofore were impossible to build [16].

After winning the design, Donald Grieb began work on the project in 1958, and looked to a visionary architect/engineer of his day, Buckminster Fuller, whose signature geodesic domes had gained international repute and were already employed in conservatory designs elsewhere. In particular, the Climatron in St. Louis, the first geodesic dome to be used as a conservatory, was designed concurrently by T. C. Howard, of Synergetics, Inc., Raleigh, North Carolina, incorporating the principles of R. Buckminster Fuller.

Grieb, in an interview he gave when he was 90 years old, recalls an early attempt to get Fuller's design team onboard: "I asked them if they'd like to join hands with me in designing these domes," Grieb says. "They sent an attorney out and he made it clear their system was one they didn't want to work on with another architect. So, they were off the list." [3] Called glorious "glass bubbles" in early headlines, the beloved bumps in the landscape are often likened to the geodesic domes popularized by Buckminster Fuller, which represented a single, elegant design idea and immense structural integrity. While they share an aesthetic kinship, Grieb's beehive-shaped domes were distinct and fundamentally fussier, adding layers of inventiveness [16]. Ultimately, Grieb served as the sole architectural force behind the Domes and partnered with engineer, Charles Whitney to make the project a reality.

Note that in from 1960 – 1970, Grieb was prolific and his name seemed to be on everything in Milwaukee, from small projects like schools, office building and homes to several high-profile projects. These included the 1965 Amtrak depot, the 1968 Milwaukee Courthouse Annex and the 1969 Milwaukee Civic Center Plaza. Much of that legacy is long gone as structures have been demolished, and those that remain are largely altered or in a state of disrepair [16]. Vincent James, an internationally recognized architect based in Minneapolis, made a pilgrimage to visit Grieb in the 1980s when he was living in Arizona. James was a young architect then and Grieb was woefully out of fashion. "Grieb was a self-styled visionary, as idealistic as he was idiosyncratic," says James today. "I am confident the Jetsons would have loved some of his buildings. But the Domes are his great contribution to the city of Milwaukee" [16]. Moreover, they are one of his few remaining projects.

2. Mitchell Park Domes

2.1 History

In 1898 crews began constructing the first, original Mitchell Park Conservatory and greenhouses to propagate its plants. It was considered a "Victorian glass house." It was built by Charles Koch, who also built Milwaukee's City Hall [17].

According to Friend of the Domes website: In 1898 construction began on the Conservatory under H.C. Koch and Company's super-vision. The landscape architecture was by Warren Manning. The structure paid homage to the Crystal Palace in London, England. People gravitated to Manning & Koch´s design in Mitchell Park. "Because of the conservatory and the sunken garden and just the flowing pathways, it became known as Flower Park. At one point, it was considered the most popular destination for people taking the streetcar to go and spend an afternoon enjoying the flowers, promenading — that went on for quite a few decades," As for the conservatory, it was well-loved, but not well-tended and ultimately, yhe structure was demolished in 1955 [17].

Figure 4: Original Mitchell Park Conservatory (Credit Milwaukee County Historical Society)

Subsequently Milwaukee County started to make plans for a more modern, new Conservatory. It was the beginning age of space travel; it was the age of general optimism and of the belief that technical progress would transform society and the world in general into a better place. Milwaukee's vision was to replace the old conservatory with a signature building that would stand for this positive, technical, progressive belief as a credible symbol [18].

2.2 Design Process

The problems in the design of the domes were significant – and almost prohibitive. The curve of the domes had to be at a certain degree to permit the proper amount of light ray penetration for good plant growth. But this angle had to be balanced against condensation drip and high humidity, discomforting aspects of most green houses, which had to be mitigated in order to give the viewing public inviting atmospheric conditions. With these basic considerations, Grieb designed the complex conoid as a single layer space frame and then copyrighted the configuration. [2]

The basic design criteria were determined by the horticultural function of each dome. In both the tropical and arid domes, a maximum amount of sunlight is required to produce the best possible examples of full-sized plants, such as rubber trees, palm trees, and banana trees as well as various species of cacti. To provide necessary sunlight at the Milwaukee latitude (43º North), and considering the many days the sun does not shine during the winter months, it became necessary to devise a method of concentrating the sun's rays so that full sized tropical and arid trees and plants be supplied with the necessary ultraviolet rays of the sun's spectrum so vitally needed for photosynthesis in plant growth. A second, and equally important requirement in the design of the structure dictated that the inside of the dome be free from high humidity and condensation to present the most inviting atmospheric conditions for the viewing public. With these two basic considerations, Grieb laid out the three complex conoidal domes and proportioned and grouped them with their connecting foyers in an outstanding and revolutionary approach to the public display of horticultural beauty. [2, 3]

Having furnished such a design, Grieb requested that the domes' surfaces permit 75% unobstructed light to enter. He left it to the engineers of Ammann and Whitney to work out the details to meet these requirements. Crews began constructing Grieb's vision in 1959 — first the Show Dome, followed by the Tropical Dome, and finally the Desert Dome in 1967.

2.3 Performance of Constructed Facility

A report of an investigation conducted 1994, so almost 30 years ago, states the following: "According to the Milwaukee County records, the domes have required very little annual maintenance. The domes have performed satisfactorily for 30 years but are now showing signs of age. A variety of deficiencies that affect functionality and operating costs have been identified. These deficiencies will only increase if maintenance is delayed" [8].

About the concrete structures the same report says: "A pattern of concrete cracks appear in each of the domes. These cracks appear typically where two separate precast pieces were connected during construction. The cracks, although unsightly, appear to be only superficial in nature… Currently, the concrete appears to be in good condition based on the testing performed, but without adequate protection the concrete can deteriorate causing significant structural problems in the future. [8]. At the time of this paper, another 30 years have passed, and the recommended maintenance has not been performed. Instead, stop-gap mitigation has been applied in hopes of delaying the deterioration.

A more recent report from 2017 [7], adds the observation of concrete debris falling down: "Based on our walk-through observations and review of previous reports, the precast concrete framing appears to be in fair condition and consistent with long-term exposure to moisture and the environments within the domes. The primary issue is spalling concrete at the embedded connections, which appears to be the result of shallow concrete cover, corrosion of embedded plates, and cyclic temperature changes. Shallow concrete cover on the sides of the embedded plates makes the concrete susceptible to spalling as originally designed. Installation of a netting system has mitigated concerns with spalling concrete."

Falling concrete debris and water leakage during rainfalls have led to temporary closings to the public, and to the installation of safety nets underneath the dome structures [7, 8]. These nets obstruct further the sunlight and prevent glass cleaning and maintenance from the inside. This combination led to severely reduced transparency with some impact on the plant life within the domes.

Several studies and reports on the domes' condition were done over the past decades [5-8]. Meanwhile there had been some minor repairs, but the overall cost for a thorough renovation is ever increasing, according to these studies. Public funding is limited and there are discussions about private fundraising, and even rededicating the use of the domes to be run by public-private partnerships. A speaker for "The Domes Task Force" says: "That the county and all of the partners are absolutely committed to urban Milwaukee and making sure that we're doing everything that we can to stay up with stewardship, the environment ... but we're also very committed as a community to economic justice and community economic development" [7].

3. Structural System

3.1 Structural Grid-Shell Topology

Antecedent architectural projects for the Mitchell Park Horticultural Conservatory include: Missouri Botanical Gardens, Phipps Conservatory & Botanical Gardens, Lucile Halsell Conservatory and the nearby Garfield Park Conservatory [19]. However, structurally, geodesic domes and space frame structures (e.g. "trussed frames") like the Schwedler (1875), Zimmerman (1901) and Schlink (1907) domes all provide precedent for the work of Grieb and Whitney [20].

Most significantly, in 1954, Buckminster Fuller received a patent for what is now known as a "Fuller Dome" based on his "Bucky-ball" ideas. This method was reified in 1959 as a geodesic steel dome in Louisiana and provided additional inspiration for the space frame topology which would be used for The Domes.

All the examples mentioned used steel sections that are connected via special joints. The system developed by Grieb and Whitney utilized concrete instead. In fact, according to Robert Hopwood, manager of the Milwaukee office of Ammann & Whitney: "Almost at the outset, we decided to use concrete on this structure as the most practical material to resist…moisture…inside the domes." [3] The switch of material coupled with the unique geometry resulted in a truly novel spatial framework. The geometry of the conoid is triangulated using a series of modules as shown in Figure 5. These modules were further simplified to result in reusable formwork for the precast members [4].

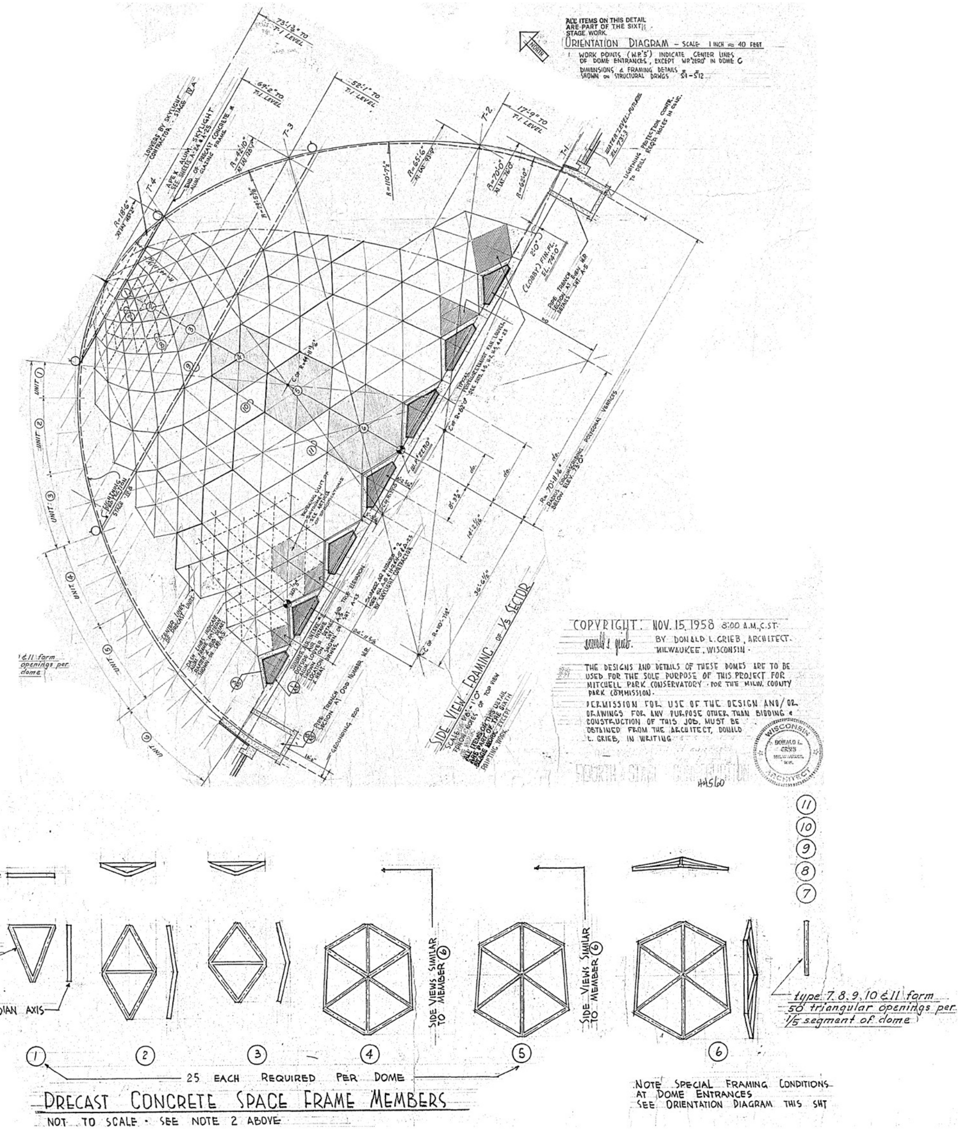

Figure 5: Space Frame Layout and Triangulated Modules

As a result of the concrete material and the spatial framework topology, the resulting structure reduces the beam thickness required (compared to other geometry) and also increases daylight transmission, decreases structural weight-to-strength ratio and results in repetitive and flexible construction [2]. Of particular import is the fact that the conoidal shape results in greater curvature at the apex resulting in improved drainage (both exterior moisture and interior condensate) as well as reducing the snow load on the roof [2].

The design of the structure did not use the kinematic spatial framework theory that has been advanced by Muller-Breslau, Mohr and Foppl. Rather, according to Hopwood [3, 4], the design leveraged the initial approximate form of a smooth dome surface using the radial and hoop stresses to obtain approximate principal stresses. The surface was then replaced with an initial pattern and the members where checked for utilization of the resolved principal stresses along the members. The patterns were iterated until a topology was obtained that met both the structural demand as well as architectural (i.e., daylighting) and aesthetic requirements.

The structural demand was based on a 1.44 kPa vertical load (associated with snow load for Milwaukee, WI). Subsequent analysis has shown the utilization of the structural members to range from 68% to 77% of capacity. This indicates the relative conservatism associated with the simplified design method used by Whitney and Hopwood, but also highlights the residual strength benefits over the lifespan as deterioration has set in.

3.2 Design Process and Constraints

Successful delivery of the project required cost efficient construction methods for a complex structure. As a result, the totality of casting, handling and erection was left to the discretion of Hufschmidt Engineering. Since the formwork and labor proved to be significant, according to Hopwood, "it was decided to detail the dome for precast handling…to create the smallest number of members and at the same time provide the greatest re-use of forms" [3, 4]

Construction engineering resulted in a method for casting the modules similar to that used in foundry work. Since the modules were not planar (as shown in Figure 5), the forms utilized a double pour method with a sacrificial Plaster of Paris series of insets that were later removed for the final connecting pour. The process of casting and removing the modules is shown in Figure 6.

These precast modules were then assembled over a falsework with the connection joints consisting of welding the exposed #6 to #9 rebar to a 9.525 mm plate which was then grouted to complete the connection.

Figure 6: Onsite casting of concrete modules (screenshots from Supersky Video)

Façade System

4.1 Façade Overview

The existing glazing system is an intricate glass and aluminum enclosure that still constitutes, after 60 years, an aesthetic and functional system of exceptional beauty and innovative value. Grieb started 1957 with the design of the conservatory. Early on the company Supersky was called in to join the design team for developing the concept for the glazing system. The final concept for the glazing system was codified in May 1960. Each larger triangular opening of the concrete latticework is covered with 4 smaller triangular glass panes as shown in Figure 7.

Figure 7: Triangulated façade system showing aluminum glass components

The subdivisdion for the glazing was based on available glass sizes for the wire glass. The cladding consisting of rafters, hubs, and glass is sitting on the concrete structure as a skin system. This skin system is not carrying global loads of the dome, but simply carries the local wind loads and gravity loads from each triangular glass panel into the concrete beams directly underneath as shown in Figure 8.

Each glazing rafter has a dual function; it carries the lateral loads from the glass into the hubs (which look like space frame nodes), and second each rafter is hollow drainage tube and transports the water from the hub above downward to the next hub below. Along its length the rafter collects moisture from condensation at the inside of the glass , and it collects intruding water from rain that may enter the seals on the outside of the glass. Especially the covers of hubs created pockets that were potential inlets for water. The hubs are hollow, anchored on the concrete beams, and are the structural supports for the rafters. The hubs are receiving water from the rafters above, and they are drained by the rafter below the hubs. Thus the hubs and rafters are establishing a network of water lines from the top of the dome all the way down to the perimeter.

Figure 8: Model of the nodes (left) and in-situ photograph of nodes circa 2020

The rafter connections to the hollow hubs are designed in two different ways: the rafters coming in from above are sliding in an opening of the hub, thus allowing thermal and local movements without creating axial forces in the rafters. The rafters connecting at the lower part of the hub are fixed sealed and with rubber seals so to avoid water leaking when it runs out of the hub into the tube part of the rafter.

4.2 Installation of the Glazing System

Supersky prefabricated the aluminum-glass skin system in larger segments. Each segment was mounted on an adjustable steel jig, surveyed for precision to match the theoretical dome surface, and then lifted as shown in Figure 9. Each hub (node) is equipped with a two-part telescopic standoff that is adjusted to its correct position and then welded the stainless steel embed plates on the surface of the concrete beams.

Figure 9: Module being mounted (left) and lifted into place (right)

4.3 Integrated Moisture Capture and Façade Support

One of the main objectives was to design the system such that it should be capable of removing completely any condensation water that would form on the interior surfaces of the glass panels. Per Patent No. 3192669, the patent owner is Supersky employee Ronald G. Hawkins. [1]

The description of the patent provides detailed system function:

> "The rafters are constructed to collect and drain condensate from the inside surfaces of the skylight. For this purpose fins may be provided on the rafter or on the glazing strip for collecting condensate and directing it into a hollow hub, or into the tubular rafter. The lower portion of each rafter is made tubular and enters the hollow hubs at opposite ends to serve as part of a tubular network for draining condensate.
>
> Each rafter is secured at the upper end and sealed to the corresponding hub, and is loose to freely slide into the hub at the lower end to provide for necessary expansion and contraction of the rafters without distortion of the skylight. A universal connection preferably in form of a ball and socket joint secures the rafters and has a pair of sealing gaskets to close the opening in the hub.
>
> To collect the condensate, the glazing strip beneath and along the edges of the glass toward which condensate tends to run, is provided with a gutter which receives the condensate and conducts the same downwardly along the rafter and into the hub at its lower end…
>
> The hubs of the skylight in addition to acting as a distribution center for water flowing thereto serve as reservoirs in case of high condensate runoff from backing up and overflowing the troughs along the rafters…
>
> The invention has found particular adaption and is herein illustrated as applied to a large dome for a botanical conservatory. In this use it is desired to provide transmission of better than 90% of the light and it is estimated that the present invention provides for transmission of as high as 94% of the total light."

Figure 10 illustrates the collection of condensation water and of rainwater leaking into the pressure cap of the rafter, and flowing within the rafter into the next hub below. The opening in the hub for the rafters from above are not sealed so the water can flow freely into the hub. The rafters draining water out of the hub are carefully sealed, and the water is drained downwards through the tubular part of the rafter. This detail is essential for the façade system as the existing glazing system is designed around massive amounts of condensation water, to be collected and safely drained to the perimeter.

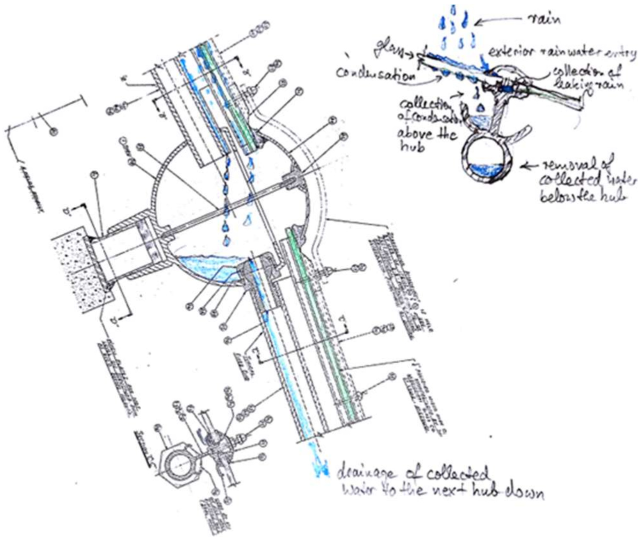

Figure 10: Author illustration of the patented façade system

4.4 Façade Performance after 60 years

Despite its intriguing design the current system has a lifespan that is long, but not unlimited – particularly without proper ongoing maintenance [21].

The aging of the polymer seals is the main reason for its progressive failure in the form of leaks. A second reason for apparent failures is the wire glass. The failure is re-occurring glass breakage. It is in the nature of annealed glass that there is slow but inexorable growth of micro-cracks which causes macro-cracks sooner or later. Optically the surface of the glass becomes dull which cannot be removed by cleaning. It speaks for the high quality of the original glass that after almost 60 years there are still so many intact original glass panels. A third reason for the observed deterioration is the existence of pressure caps on the surface which causes water to sit in the pockets formed by these caps, finding its way inside over time. This rainwater, finding its way through leaks into the interior, was seemingly not the main concern of the designers of the original system. The gaskets on the hub covers are not compressible enough to accommodate the necessary sealing needed at the pressure plate end closures. The pressure plate gaskets have hardened to a point where they do not properly seal to the glass thereby letting water enter the system. There are missing pressure plate fasteners, missing hub cover gaskets, missing hub covers, open flashing splice gaps and holes and cracks in glass lites. The sealant efforts that have been taken to seal the hub cover gaskets are marginal with many voids and gaps still allowing water in at the hub covers. The extruded aluminum frame components appear in good condition with no corrosion or degradation that would prevent them from functioning structurally. There are, however, varying degrees of internal debris and clogging due to drainage residue that does affect the draining function of the hollow extrusions. The physical threaded connections between the "down" members and the hub are good, however the condition of original rubber gasket systems (intended to make these connections water-tight) varies from functioning to complete failure. The hollow aluminum hub bodies are in good shape with no corrosion or degradation, however in many locations they are damaged [6].

5. Summary and Conclusions

The Mitchell Park Horticultural Conservatory "Domes" are a significant structure for their cultural, structural and architectural accomplishments. Designed by Grieb and Whitney, the Domes represent the only space frame structure constructed by either designer. These Domes are unlike any other domes in the world and, due to patents, were never replicated. The iterative design approach between the architect, engineer and contractor resulted in a true integrated design which resulted in 2 patents for the structural and façade systems. Additionally, the Domes reflect sensitivity to the programmatic demands:

architectural aesthetic, structural performance, mechanical conditioning, façade integration all of which resulted in a historically unique structure which was not surpassed in architectural/engineering integration, optimization or efficiency for nearly 60 years [22].

After over a half-century of use and deferred maintenance, the Domes, like many other mid-century shell and space frame structures are beginning to deteriorate [21]. This report collects and presents the information associated with the design, delivery and subsequent forensic studies to preserve the information about these structures for broader dissemination and study as well as serve as a baseline for future investigations

Acknowledgements

All images are either in public domain – courtesy of the Milwaukee Historical Society or are the authors.

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