Abstract

GALLION, FRANKLIN CORDELL. Manufacture and Field Test of a New Adaptive Shading Technology: A Case Study. (Under the direction of Dr. Larry M. Silverberg.)

A field test of a new adaptive shading technology called the powerblind was performed on the campus of North Carolina State University. The manufacturing team evaluated every aspect of the design implementation from component manufacture through field testing. This evaluation was intended to guide future evolutions of the technology by answering the most basic question: “What has the Talley Student Center experience taught us about the technology and its future?”

A set of eight powerblind units, each measuring approximately three feet by five feet, were manufactured and installed in the Talley Student Center Boardroom. Work began with an existing design template. Component manufacture was performed during the fall semester of 2000. Manufacturing system development, troubleshooting, and unit assembly were completed during the first half of the 2001 spring semester. Installation, final troubleshooting, final delivery to the customer, and a public unveiling were completed in the second half of the 2001 spring semester.

It was concluded that the technology works in a real-world setting. Although some quality problems existed in the final delivered product, the reason in each case was well understood, and potential avenues for solutions presented. It was also concluded that the product could be mass-produced to sufficient quality using relatively low-technology tools and techniques.
MANUFACTURE AND FIELD TEST OF
A NEW ADAPTIVE SHADING TECHNOLOGY:
A CASE STUDY

by

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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Master of Science

Mechanical Engineering

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Dedication

For Molly, Jack, and Helen.
Franklin Cordell Gallion was born to Jackie Lee and Molly Anna Gallion in 1968 in North Wilkesboro, North Carolina. The family moved in 1973, and Frank spent his formative years in the middle of Wake County, NC. His father, Jack, and Grandmother, Helen, died in the spring of 1979. Frank, his mother, and his two younger sisters, Jackie and Laurel, were on their own.

Frank graduated from Garner Senior High School in 1986, and began a four-year enlistment in the Navy in 1989. He visited many places across the United States, the Pacific and Indian Oceans, and the Middle East. He sailed with the USS Cape Cod (AD-43) in support of Operation Desert Storm and to assist the Subic Bay Naval Base after the historic eruption of Mount Pinatubo in 1991.

Beginning with independent math studies while in the Navy, as well as a year spent at Wake Technical College, Frank was able to overcome his extremely poor high school marks (1.87 GPA), and gain acceptance to the Mechanical Engineering program at North Carolina State University in 1994. He funded his education by living at his mother’s house and working as a waiter, busboy, plumber, engineering tutor, and co-op student. He also helped his family turn a small profit on their small trailer park in rural Garner.

In the fall semester of 1995, Frank learned engineering dynamics from Dr. Larry Silverberg (what a tough class! He got a B!). In the fall of 1997, Frank gained his first exposure to the powerblinds product. He built a powerblind prototype in which the slats were place in a vertical orientation. This design has yet to be put into practice.
Frank graduated with a BSME in December 1997 with a final GPA of 3.36, and was promoted from co-op student to manufacturing engineer at a tier-one constant-velocity joint manufacturer in Sanford, NC. There, he did ‘whatever it took’ to make CV joints for major automobile manufacturers. The work was rewarding, yet amazingly chaotic and stressful.

Frank met his future wife, Anne Mullins, in January 1998 (they were married on September 30, 2000), and the couple decided it would be a good idea for him to go back to school. Frank called on Dr. Silverberg, who told him about a new Master’s Degree program which concentrated on mechatronics as well as a little project he was working on with electrostatic levitation.

Graduate school was paid for with the kind support of the taxpayers of North Carolina, monetary gifts from family members, the profits of his wife’s massage therapy business and a complete liquidation of Frank’s savings. The 60 mile, hour and fifteen minute one-way commute to school wore Frank out and helped to put a whopping 39,000 miles on his wonderful 1992 Camry between January of 2000 and August of 2001. Frank is almost officially ‘smartified’ and is scheduled for graduation in December of 2001.
Acknowledgements

Thanks to my wonderful wife, Anne, and her family for their love and support during my graduate studies.

Thank you to Mrs. Evelyn Reiman for having the courage and foresight to let a pack of mad scientists use her boardroom as a laboratory.

Thank you to our corporate partners: Arch Aluminum, Collmer Semiconductor, and Aimet Technologies, who donated materials and know-how.

Last, but certainly not least, thanks to all the people who worked so hard to make the project a reality: Joe Corey, Mathew King, Richard Michelli, Amit Aagarwal, Vanapeth Saysom, Dr. Chau Tran, Joyce Sorensen, Carol Hubbard, Attreyo Chatterjee, Greg Rhequate, Keith Sanders, Chris Canaday, Glen Spadin, Brandon Sink, Andrew Forrest, Julian Samuel, Mike Breedlove and Skip Richardson, the housekeeping and maintenance staff of the Talley Student Center, Gray Davis, and Nathan Etheridge.
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“Why hast thou left the light of sun, 
thou poor one?”  
(Homer, The Odyssey)

Sunlight is essential to the health and well being of human beings (Lillyquist 2). Heliotherapy (or sun-medicine) appears in the oldest known medical text (Reid 247). Full-spectrum sunlight has been used in the 19th and 20th centuries to aid in the cure of rickets and tuberculosis (Lillyquist 18, Mayer 68). Present-day research has reaffirmed the medical significance of sunlight. It aids in the function of the liver, can reduce high blood pressure, and is necessary for both the production of vitamin D as well as the operation of the pineal gland. It is clearly desirable to maximize our exposure to sunlight, although not direct sunlight.

The artificial lighting of interior spaces was integral to the explosion of scientific and industrial power in the 20th century. The health effects of long hours spent under low-intensity, narrow spectrum artificial light, however, are not well known.

In Building Energy Efficiency, the Office of Technology Assessment has reported that the single largest consumer of electricity in the commercial sector is artificial lighting (50), and that natural lighting has a potential energy savings of 59%-70% over artificial lighting (57). Keifer has reported that lighting, heating, and cooling accounts for seventy-one percent of energy use in commercial buildings (1).
The infrared radiation present in sunlight transmits heat to the interior spaces it shines upon. Predicting a definitive quantity on the amount of heat radiated to any interior space through window sunlight is difficult. The illuminated area is constantly changing, and many independent factors affect the intensity and absorption of the sunlight. For example, the total heat absorption from ‘window sunlight’ for a single-family dwelling called the ‘1973 house’ placed in Chicago and Houston was measured as 5% and 24%, respectively, of the total internal heat generation (United States Congress, Residential Energy Conservation 33).

Measurements of the afternoon sunlight at the Astro-physical Observatory in Washington in 1902-3 yield an average of 1.24 small calories per cm² per minute, or 274 Btu per ft² per hour (Atkinson 58). This corresponds to 0.023 ton per ft² of window area. Obviously, the interior space of a building is not perfectly absorptive, and the actual heating value of the sunlight will be some fraction of the total available transmitted energy. However, consider that a typical 5 ft by 5 ft window facing the Sun in Washington during the time the measurements were taken would transmit a total of just over ½ ton of potential heating power. Also consider that a typical 2,150 square foot house has a cooling load in the 3-ton range. (Cengal & Boles 585)

Clearly, the health benefits and the energy savings found in the sunlight that enters through an ordinary window are significant. The question then arises as to how to take better advantage of ordinary sunlight.
The fundamental problem associated with bringing more sunlight to interior spaces is associated with its time-dependence. While natural light is attractive most of the time, direct mid-afternoon sun can be harsh and bothersome. The control of the light entering an interior space requires an adaptive system. In order to compete with artificial light, the natural light entering the interior space would need to be able to be turned on and off as easily as artificial lights; the shades would need to be switch-operated. In this thesis, the term adaptive shading refers to switch-operated systems.

An adaptive shading system was developed at North Carolina State University several years ago (Silverberg 1). The technology was reduced to practice (Kiefer 1), methods of analysis were developed (Kiefer and Silverberg) and methods and tools for commercial production were developed (Pakala), (Agarwal).

At the point where work for this thesis began, the technology had not been subject to any tests outside the laboratory. Many questions remained unanswered and unknown. The purpose of the work presented here was to take this simple idea from the laboratory into the real world, solve as many problems as possible on the way, and get a closer look at the ones that could not be solved immediately.
2 Background Information

The adaptive shading system developed at NC State is called the powerblind. It consists of a venetian blind sealed between the panes of insulated glass. The blinds open and close electrostatically based on the teachings of a patent (Silverberg, 1). The electrostatically actuated blinds replace the manually operated system along with its pulleys, gears, and gear box. The first opportunity to field-test the powerblind arose in a request to retrofit a boardroom at NC State’s Talley Student Center with a wall of 16 powerblind windows. I was asked to direct the job and to document the findings in a written thesis. The direction of the Talley Student Center job put me in a unique position to assess the production process, from part production and assembly to final installation.

In January of 2000, we inherited a room full of parts and equipment, and some “tribal knowledge” left over from past teams of students who had helped develop the powerblind. The powerblind was beyond the design phase, and our new team struggled to figure out how best to accomplish the next step - design validation. It was decided that a field test was our best chance to answer many questions about the “real-world” performance of the powerblinds.

What would the production issues be with making parts, assembling units, and installing them in a building? Could these steps be performed reliably, with an acceptable level of quality? Were the specifications and material choices adequate for field service? Could units large enough be built? How long would the production steps take to complete? What would be the public’s reaction to the system? How well would the system perform with daily consumer use, and for how long?
Both simple and difficult technical problems were anticipated. A major goal of the project was to discover and document everything possible about potential issues, quality control, and improvements to part production, assembly, and installation. We were vulnerable to both simple and hypertechnical electrical problems because of the team’s general lack of expertise in electrical engineering. Unforeseen problems associated with manufacturing tolerances, tolerance stack-up, material selection, and simple to complex electrical phenomena were uncovered and solved.

After the decision was made to perform the field test, our team would need almost a year to get organized, hire workers (hardworking undergraduate students in mechanical engineering), produce the needed parts, assemble the units, perform the needed testing, and finally install the units at the Talley Student Center.

A simple critical-path management plan was used in order to guide the entire production process. Weekly planned meetings were held, and detailed lists of activities were drawn up in advance. The concurrent tasks versus the consecutive tasks were continually inspected. Manpower requirements, required time and materials, and lead times were continually checked. The job divided neatly into four phases: material procurement, part and equipment manufacture, assembly, and installation.

The design of the powerblinds had been worked out in great detail, many prototypes constructed, and exhaustive laboratory tests conducted. However, these units would be built with some relatively new design changes. Units had never been constructed of these dimensions or quantities before. Production had never had anything resembling a formal deadline before. Unexpected problems and incorrect manufacturing time estimates were absolutely expected. These uncertainties were compounded by the fact that each team member had a job, a full course load, or both. These problems were countered first and foremost by an acknowledgement of the underlying uncertainties and liberal padding of the production schedule.
It followed that our shop time was quite valuable, and progress was at a premium. The guiding principle adopted for all of the powerblind activities was that maximum productivity and a high quality product would be achieved with a production process that, rather than focusing on expenditure of effort, focused on minimizing scrap and waste (Deming). This guiding principle, along with the needs for safety, teamwork, and staying well ahead of the posted schedule in anticipation of unknown problems were stressed to each of the team members from their first meeting with the project leader (the author), and periodically throughout the project.

Because the part manufacture and assembly processes would be done in the same shop space, it was decided to begin the assembly stage only after the part manufacture was completed. The fall 2000 semester was dedicated to planning, hiring, and training the student workers, gathering the required materials, and making the required parts. Over 160 feet of ladder material was made, one inch at a time, on a die punch which was manually loaded, actuated, cleared and indexed. About 3000 tabs were made one at a time on a small plastic injection molder. An experienced operator could make one tab in 20 seconds. It was originally estimated that 2350 tabs would be needed, but 3000 were made in anticipation of scrap. When the assembly was complete, less than 100 tabs remained.

The spring 2001 semester was dedicated to assembly and installation. A schedule for the semester’s production was constructed by working backwards from the due date. Considerable time was spent recruiting, interviewing, and training more workers. The assembly of the first units required four workers and eight hours per worker per window. The sixteenth and final unit was three times larger than the first, and was assembled by two workers in just two hours.
The most significant setback occurred on March 13 when the smaller units (a total of eight) were found to experience a problem that we called “flutter.” After sealing the first eight units, we observed that individual slats in the window would flicker uncontrollably for a short period after which a different slat would flicker, and then another and another in no apparent pattern. This had never before been observed, and the cause of the flutter was never fully understood. Since these windows were already sealed and there was no time to solve this problem, it was decided to only install the larger units (eight in all). On a serendipitous note, during installation there was barely enough time to install the eight large windows, let alone the other eight small windows. This problem of flutter, like the others, was troubleshot very carefully when it arose in order to ensure a quality result and on-time delivery.

The eight larger powerblinds were installed in the fourth-floor boardroom of the Talley Student Center and they became fully operational on April 11, 2001. With the great care that was taken during part production and assembly, slightly more than 99% of the slats functioned flawlessly. Slightly less than 1% of the slats periodically experienced a “sticking” problem. A tiny amount of residual dust and dirt was left inside the sealed air spaces. The electromechanical performance of the units has not changed to date.
Figure 2.1: Installed Powerblind Units in the Closed Position

Figure 2.2: Installed Powerblind Units in the Open Position
3 Part Information

The most important functional parts required to manufacture the powerblind units are described with the following table and illustrations. Note: ‘IG’ refers to insulated glass, ‘HV’ refers to high voltage.

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Function</th>
<th>Production Method</th>
</tr>
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<tbody>
<tr>
<td>Tempered Glass</td>
<td>Seals the inside of the assembly, provides insulating air space.</td>
<td>Commercially produced for IG industry</td>
</tr>
<tr>
<td>Low-emissivity Glass</td>
<td>Attracts slats to open position with induced charge. Seals the inside of the assembly, provides insulating air space.</td>
<td>Commercially produced for IG industry</td>
</tr>
<tr>
<td>Sealant</td>
<td>Seals the inside of the assembly, provides insulating air space.</td>
<td>Commercially produced for IG industry</td>
</tr>
<tr>
<td>Air Spacer</td>
<td>Provides structural spacing between glass panes and support for sealant. Provides path for HV actuation signal to hooks, ladders and slats.</td>
<td>Commercially produced for IG industry. Cut to size with chop saw.</td>
</tr>
<tr>
<td>Aluminum Foil Tape</td>
<td>Provides low resistance path for HV electricity around air spacer.</td>
<td>Commercially produced for HVAC industry</td>
</tr>
<tr>
<td>HV supply wire</td>
<td>Provides insulated path for HV signal from the power supply to air spacer.</td>
<td>Commercially produced for HV power supply industry</td>
</tr>
<tr>
<td>Ground wire</td>
<td>Provides insulated path for induced actuation signal to low-emissivity glass.</td>
<td>Commercially produced for electronics industry</td>
</tr>
<tr>
<td>Hooks</td>
<td>Support the ladder, slit, and tab subassembly. Provide path for HV actuation signal to ladders and slats.</td>
<td>Manual die punch</td>
</tr>
<tr>
<td>Tabs</td>
<td>Locate and support ladder and slit assembly between panes of glass.</td>
<td>Manual plastic injection molder</td>
</tr>
<tr>
<td>Ladders</td>
<td>Locate and support slats in air space. Provide electrical path for HV actuation signal to slats.</td>
<td>Manual die punch</td>
</tr>
<tr>
<td>Slats</td>
<td>Rotate to either block or transmit light.</td>
<td>Commercially produced for venetian blind industry. Hole for ladders produced with manual die punch</td>
</tr>
</tbody>
</table>
Figure 3.1: Close-up of Slats, Ladders, Tabs, and Air Spacer

Figure 3.2: Side View of Slats and Glass in Closed and Open Positions
The assembly of the powerblinds for the Talley Student Center was performed with the aid of three new tools, developed specifically for this evolution. They were: a series of backing boards, a rotating table, and a hole punch for the hooks.

The purpose of the backing board was to support the slats, ladders, and tabs during the assembly process. The backing boards needed to be lightweight, thin, reasonably rigid, and easy to clean. The selected backing boards were 1/4" thick sheets of foam insulation (otherwise used for thermal insulation).

Figure 4.1: A Backing Board
The rotating table greatly simplified the glass installation process. It was developed to improve the safety and quality of the assembly process by reducing the physical effort required to make a powerblind, as well as reducing the potential for damage to the slat, ladder, and tab subassemblies.

Figure 4.2: The Rotating Table
The hole punch for the hooks was a small tool that enabled the hooks to be connected to the top air spacer with ease and precision. The tool would line up on a pencil mark offset from the desired hole location and punch a perfectly sized hole perfectly offset from the centerline of the air spacer.

The conceptualization, design, and construction of both the rotating table and hole punch were accomplished by team members, with special help from the Broughton Hall machine shop staff. Both presented unique technical challenges to the team members, and each was an interesting story in its own right.
The remainder of this section walks the reader through the assembly process for the purposes of illustration and familiarization, summarized in Table 4.1:

Table 4.1: Sequential Order of Assembly

<p>| | |</p>
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<tbody>
<tr>
<td>1.</td>
<td>Clean and prepare the work area.</td>
</tr>
<tr>
<td>2.</td>
<td>Set up the rotating table.</td>
</tr>
<tr>
<td>3.</td>
<td>Assemble the slats, ladders, and tabs.</td>
</tr>
<tr>
<td>4.</td>
<td>Remove the slat racks.</td>
</tr>
<tr>
<td>5.</td>
<td>Assemble the air spacer.</td>
</tr>
<tr>
<td>6.</td>
<td>Install the air spacer.</td>
</tr>
<tr>
<td>7.</td>
<td>Install the glass.</td>
</tr>
<tr>
<td>9.</td>
<td>Seal the unit.</td>
</tr>
<tr>
<td>10.</td>
<td>Store the unit.</td>
</tr>
</tbody>
</table>

Before beginning work, each team member was expected to be familiar with the correct orientation of all components. Every component except the un-laminated glass and corner keys had a unique, often hard to differentiate, orientation for proper unit operation. One of the best tools in the shop was an assembled, working unit on display for reference during assembly.

**4.1 Clean and Prepare the Work Area**

The shop was quickly cleaned and all tools neatly arranged. Any scrap was discarded or defaced. The backing boards, rotating table and surrounding areas were cleaned. The team members were encouraged to wash their hands before beginning work. At the end of the day a similar ritual was practiced. Scrap was discarded or defaced, tools were returned to their places and equipment and workbenches were wiped down. Even with these procedures, dirt and grime showed up in unexpected places.
On one occasion, a modification to the slat racks was being tested for the first time. The slat racks were first wiped down. The slats, ladders, and tabs were then assembled. When the rotating table was rotated and the slat racks removed, they dumped about three tablespoons of fine plastic dust onto the complete subassembly. The previously unnoticed dust had been deposited in the grooves of the slat racks during the machining process. The team lost about six man-hours removing the dust from the fragile subassembly. In the end, a total of two fingerprints, four pieces of dust, and three small marks contaminated the eight installed units.

4.2 Set Up the Rotating Table

The table was initially set and locked in the horizontal position. The restraining bars needed were pinned down and the remaining restraining bars were stored nearby for easy access. A backing board was placed on the table and received a final wipe down. At this point in the original procedure, the assembler received the following reminder:

Cleanliness of the interior of the window is of equal importance as proper electro-mechanical operation. Be very conscious of keeping the area clean while assembling the windows.

Do not, for instance, allow someone to sweep, use aerosol cans, or eat near you while a slat/ladder/tab assembly is exposed to the shop air. Do not allow use of the chop saw or any other dusty or dirty activity while the slat/ladder/tab assembly is exposed to the shop air.

Make sure that you cover the slat/ladder/tab assembly if you will not be working on it for even a few minutes or before you take a break. It takes a lot of wasted time and effort to clean a soiled slat/ladder/tab assembly. Wash your hand before beginning this work, even if they look clean.
4.3 Assemble the Slats, Ladders, and Tabs

Our earliest planning efforts correctly identified this step as the most time-consuming and perhaps the most difficult part of the entire assembly process. Therefore, most of our planning efforts centered on supporting timely and proper execution of this critical step. It was of paramount importance to minimize bending and twisting of the ladder while press-fitting the tabs to the ladder.

It was found that some of the workers could perform this assembly step, but most workers could not (including the author). The people who were successful tended to have small fingers, and used their thumbnail or fingernail to press the tiny piece of aluminum between the tabs’ press-fit “nubs.” There were strong personal preferences for which side an assembler would work from and which side of the tab would face the worker. Note that once pressed in, the tabs were difficult to remove.

Note that one side of the slat, ladder, and tab subassembly was designed with an offset to face the low-emissivity glass and the other to face the plain glass. The outward curved side of the slats faced the low-emissivity glass when in the closed position. Also, note that the slats, ladders, and tabs could be assembled on a backing board, either directly on the rotating table, or on another surface and then transferred to the rotating table.

This slat, ladder, and tab subassembly process began with placing two slats into every other slot in the slat racks. The slats were simultaneously inspected for cleanliness. By bunching the slats in this manner, more room was available for a worker’s fingers to press the tabs into the ladders. This was the first process-simplifying step discovered by one of the team members. This (now obvious) technique had not been available for the assembly of any of the previous prototype windows.
Figure 4.4: Slats Placed in a Slat Rack

At this point, it was double-checked that the slats were paired up, because a missing slat would waste a significant amount of time later. After the tabs were pressed onto the ladders, a missing slat would render the subassembly useless. An extra slat, on the other hand, could be cut off the completed subassembly.

The slats were lined up and the lengths were double-checked. The length of the ladder was checked, and the top of the ladder was cut at the point where it would mate with the hook. The bottom of the ladder was cut, leaving about two inches of excess length for handling purposes. The smoothness of the edges of the ladder at its contact regions (pivot points) with the slats was inspected.
Now, the ladder was slipped through the holes in the slats. This step was performed slowly and carefully to prevent bending and twisting of the ladder.

Figure 4.5: Ladders Inserted Through the Slat Holes

The tabs were injection molded using a uniformly (clear) colored lot of PET. The injection molding equipment available to the team was sturdy and robust, but primitive. The equipment introduced light shades of brown into the finished tabs, which varied greatly from batch to batch. In order to give the finished powerblind units as uniform an appearance as possible, the entire population of tabs were thoroughly mixed before assembly ever began so that the different shades were randomly distributed in each unit.
It was convenient to supply each worker with a small bowl, half-full of tabs. Each tab needed to be inspected carefully before it was pressed into the ladder. Limitations in injection molding expertise and equipment had produced a variety of defects in the tabs, such as excessive bends in the tab and missing or excess material. The rejected tabs were placed in another container for later review and possible remedy.

The tabs were pressed into the ladder every half-inch along the ladder. After the tabs were pressed into the ladders, the backs of the tab “nubs” were mashed flat with a pair of needle-nose pliers to prevent the tabs from separating at a later time.

Figure 4.6: Press-fitting a Tab to the Ladder
Due to the limitations of our die punch machine, the material chosen for the ladders was 0.016” thick aluminum. This meant that the ladders were extremely flimsy and ductile. A bent ladder could not be straightened completely, and the attempt took valuable time.

Therefore, during this step the workers were encouraged to take a short break every fifteen minutes and stretch the muscles in their hands. Mental awareness and freedom from pain or stiffness was an important quality control for this delicate task. Despite our best efforts, some bending and twisting of the ladders occurred during these operations. Minimizing deformation of the ladders contributed greatly to the overall quality and timely delivery of the finished product.

If this task was done on a surface other than the rotating table, then the completed slat, ladder, and tab subassemblies were carefully moved to the rotating table.
4.4 Remove the Slat Racks

Now that the heart of the powerblind assembly was complete, the slat racks needed to be removed from the subassemblies. It was undesirable to simply pick the slat, ladder, and tab subassemblies up off of the slat racks, because slats could easily fall out of place, the ladder could break free of the hook, and the tabs could become misaligned (general mayhem).

The rotating table was developed largely to prevent having to pick up the slat, ladder, and tab subassemblies during the assembly process. All previous powerblind units were produced without the benefit of the rotating table, which had placed a severe restriction on the length of the units. The slat, ladder, and tab subassemblies had no intrinsic rigidity, it came from being sandwiched between the two panes of glass.

The subassemblies were first double-checked for any quality defects, such as incorrectly assembled tabs, bent ladder sections, tab nubs not mashed down, defects in the ladder material, and the correct number of slats. Once this inspection was completed, the backing board was placed on top of the assembly and the necessary restraint bars placed in position. This created a ‘sandwich’ composed of, from top to bottom: the top restraining bars, the top backing board, the slat, ladder, and tab subassemblies, the slat racks, the bottom backing board, and the bottom restraining bars.

Next, the rotating table’s support legs were disconnected from the corners of the table, and the table was rotated 180 degrees. The table’s support legs were then reconnected to the corners of the table to stabilize it. The bottom of the ‘sandwich’ had now become the top. From top to bottom, the assembly now consisted of the top restraining bars (previously on the bottom), the top backing board (also previously on the bottom), the slat racks, the slat, ladder, and tab assembly, the bottom backing board (previously on the top), and the bottom restraining bars (also previously on the top).

The top restraining bars were removed, and the slat racks slowly and carefully removed from the fragile slat, ladder, and tab subassemblies.
4.5 **Assemble the Air Spacer**

Assembled air spacers were awkward to store. In order to conserve our limited shop space, the air spacers were assembled only as they were needed. If circumstances dictated that they had to be made well in advance, they would typically be hung from a horizontal bar cantilevered from a post 7 feet off of the ground. Fortunately, this was one of the quickest and easiest powerblind components to assemble.

The air spacer was first assembled into a top subassembly and a bottom subassembly. For large windows, it was preferable to not immediately join the top and bottom air spacer subassemblies. This was due to the difficulty of handling the entire air spacer while performing the delicate step of connecting the air spacer to the slat, ladder, and tab subassemblies via the hooks (covered in the next section).

The four sides of the air spacer had been cut to size well before assembly work began. Likewise, the holes for the hooks had been punched in the top piece of the air spacer using our special tool, and the holes for the mutton had been drilled in the bottom piece.

The high voltage supply wire was stripped 3 to 4 inches and then wrapped around the end of a corner key.

![Figure 4.8: High Voltage Supply Wire Wrapped around a Corner Key](image)
This corner key was inserted into the top piece of the air spacer so that no bare wire was exposed to the air. Another corner key was inserted into the top piece of the air spacer. Corner keys were inserted into the bottom piece of the air spacer. Finally, the side air spacers were connected to the bottom air spacer, creating a C shaped air spacer assembly.

Figure 4.9: Top and Bottom Air Spacer Subassemblies
4.6 Install the Air Spacer

At this point, the ladders were attached to the air spacers via the hooks. Joining the air spacer, hooks, and ladders was a delicate, time-consuming operation. As previously stated, the top and bottom air spacer subassemblies could be joined either before or after this step was performed.

The hooks were first bent into the correct shape and inserted into the pre-punched holes in the top air spacer subassembly.

![Hook Before and After Bending to Correct Installed Shape](image)

Figure 4.10: Hook Before and After Bending to Correct Installed Shape

Next, the tabs on the hooks were slipped through the holes in the ends of the ladders. The tabs were then folded completely over, thereby joining the top air spacer subassembly, the hooks, and the slat, ladder, and tab subassembly into one large subassembly. If necessary, the bottom air spacer subassembly and mutton were then attached to the top air spacer subassembly.

![Hook Installed in Top Air Spacer Subassembly](image)

Figure 4.11: Hook Installed in Top Air Spacer Subassembly
The corner keys were made of plastic, a poor electrical conductor. Aluminum foil tape was used to ensure good electrical distribution around the entire air spacer and therefore prevent large electric potentials between any of the interior components. Two-inch strips of the electrically conductive tape were applied to each outside corner of the completed air spacer assembly as well as between each end of the mutton and the air spacer.

At this point, bends and twists in the ladders were reduced by gently pulling on the bottom of the ladders and using fingers or pliers to straighten sharp bends along their length. Any other method of handling the ladders would bend or twist them.

The bottoms of the ladders were trimmed to fit the air spacer. If the ladder was too long, arcing could occur between the bottoms of the ladders and the air spacer. If the ladders were cut too short, the bottom slat would simply fall off the ladder. To remedy a ladder that was cut too short, a short piece of ladder could be spliced to the existing ladder by employing the bottom tab. A $\frac{1}{4}$" to $\frac{1}{8}$" gap between the bottom of the ladders and the bottom of the air spacer appeared to work fine.

Finally, the air spacers were squared. This was an initial squaring of the windows. They were squared again prior to and during the functional test.
4.7 Install the Glass

Ideally, the glass was cleaned just prior to installation to save time and minimize dust inside the unit. In a production environment, this operation would normally be done with a glass-cleaning machine. We did it by hand. Either way, both sides of the glass were very clean and free from scratches just before it was assembled. A final pass over the entire pane was made with a clean, lint-free towel just before it was needed.

Using latex gloves, the laminated glass was placed on top of the air spacer subassembly. The air spacer supported the weight of the glass. This was at least a two-person step. It was important to lower the glass slowly and squarely over the subassembly to avoid damage to the ladders.

A backing board was placed over the glass, and the necessary restraint bars were pinned to the rotating table. The support legs were disconnected from the corners of the table and the table was rotated 180 degrees. The support legs were then reconnected to the corners of the table. The top restraint bars and backing board were now removed, and the other piece of glass was squarely lowered on top of the assembly.

The ladders, air spacer, and glass were once again “squared.” This was a difficult process, since no two edges on the glass or subassembly were ever truly square or parallel. The curved, flimsy ladder sections were difficult to keep straight in the horizontal orientation. By squaring the subassembly throughout the process of assembling the glass, the final squaring operation was made easier. An important indication of quality was that a sufficient sealant gap exist along all of the edges and corners of the air spacer.
The unit was clamped together using spring-loaded clamps with a two-inch jaw clearance. One clamp was placed at each corner, and at least one clamp was placed every two feet along the perimeter. The clamps were cleaned so that they would not scratch the glass. A properly clamped window would not allow internal components to shift around during transport, nor allow the air spacer to bow inward during the sealant operation.

Figure 4.12: Completely Assembled and Clamped Unit Assembly
4.8 Perform Functional Tests

One restraint bar was placed at the top of the unit, and another was placed at the bottom of the unit. The support legs were disconnected from the corners of the table, and the table was rotated ninety degrees. The unit now hung in the vertical orientation similar to the final installed orientation.

The high voltage and ground leads of the completed unit were connected to an appropriate high voltage source. The high voltage lead was connected to the air spacer, and the ground wire was connected to the low-emissivity glass. Reversing these leads presented a shock hazard to the workers. Care was also taken that the high voltage lead did not touch any grounded surface, such as the rotating table.

The functional test was the last chance to find and fix any defects inside the window before the unit was sealed. Several functional checks were thus performed on each unit. Specifically, the following questions were carefully examined:

- Did all of the slats open smoothly every time the power was applied?
- Was any flutter observed?
- Was any electrical arcing observed, specifically from ends of the ladders or the muttons?
- Was there anything unusual?

After the unit was verified to be of sufficient quality, the table was turned back to the horizontal orientation, the support legs were reconnected, the restraint bars at the top and bottom were removed, and the unit was transported to the sealing area.
4.9 Seal the Unit

Our hand-mixed, hand-applied method of sealing the units required four workers. One worker mixed the sealant, two others spread the sealant into the air spacer gap, and a fourth assisted the other three as necessary. Since this was a messy and labor-intensive step, the units were sealed in batches of at least three windows, although the team tried to not let assembly get too far ahead of sealing.

In preparation for the sealing, 2” wide masking tape was applied to the perimeter of each side of the unit. This made the process of removing excess, dried sealant from the visible areas of the unit much easier. The taping could not be done at an earlier step because it would hinder visibility into the air space.

The sealant consisted of two components, which were mixed just before application. The sealant formula allowed for a working time of 16 minutes, which required sealant batches between 500 and 1000 grams, depending on the number of workers available to apply the sealant. The two sealant components had to be very carefully measured, then mixed quickly and thoroughly.

Using a putty knife, the sealant was spread into the air spacer gap around the perimeter of the unit. The flat side of the putty knife was pressed against the two edges of the glass to make the outside perimeter smooth. To eliminate air pockets, the knife pressure needed to be sufficiently high, but not too high, because the relatively flimsy air spacer would then bow inward.

This took some experience to perform well. In the first unit that we sealed, we later found that the long side pieces of the air spacer had bowed in during the sealing step, which prevented some of the slats in the center (bowed-in) region of the unit from opening and closing properly.

The sealant cured in 24 hours.
4.10 Store the Unit

Using as many workers as available, the units were transported to a storage area. The units were stored in a pre-designated location in the horizontal orientation. The units were separated from one another using clean, non-abrasive spacers, and stacked no more than eight high. Each stack was covered with large warning signs.
5 The Installation Process

Originally, the intention was for the installation to be performed by a professional glazier. This option proved to be too expensive, and it was decided that the manufacturing team would perform the installation. This proved to be a valuable experience that would be helpful in the future. The remainder of this section walks the reader through the installation process for the purposes of illustration and familiarization, summarized below:

<table>
<thead>
<tr>
<th>Table 5.1: Sequential Order of Installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Perform initial electrical work.</td>
</tr>
<tr>
<td>2. Transport the units.</td>
</tr>
<tr>
<td>3. Remove the old glass.</td>
</tr>
<tr>
<td>4. Prepare the frames.</td>
</tr>
<tr>
<td>5. Install and test the units.</td>
</tr>
<tr>
<td>6. Apply the molding.</td>
</tr>
<tr>
<td>7. Perform final tests.</td>
</tr>
<tr>
<td>8. Perform final electrical work.</td>
</tr>
</tbody>
</table>

Each of the steps is described in detail below.

5.1 Perform Initial Electrical Work

It was determined that each unit would have its own high voltage power supply. The electrical contractor determined that each high voltage power supply would be placed in a standard electrical box mounted in the ceiling above each unit. The 120 VAC input signal to the units would be connected in parallel, so that a single switch would control all eight units. Switching of the 120 VAC input signal would be done by a 12-Volt relay in turn controlled by either a wall-mounted switch or a remote control.
5.2 Transport the Units

The units were transported from the shop to the Talley Student Center in the back of a 14-foot rental truck. A special A-frame, constructed by a team member, was mounted on top of a large warehouse cart and used to transport the units up to the boardroom.

Note that due to an error in planning, the high voltage supply wires attached to the units had inadequate insulation. Moreover, this was first noticed after the units had been transported to the Talley Student Center. The high voltage supply wires were replaced with wires of the correct construction. This required a fairly elaborate repair involving cutting into the sealant, stripping the old wire, and soldering the new wire onto the old.

5.3 Remove the Old Glass

The old glass was removed with relative ease, at least with significantly greater ease than was anticipated. No screws stuck or rounded out in the process of the removal (whew!). It turned out that the glass was held in place by very brittle glue, and much of the glass broke or chipped around the corners and edges during the removal process. This may have been the most dangerous part of the project. Fortunately, there were no injuries.

5.4 Prepare the Frames

All of the old adhesive was cleaned out of the corners of the frame, and the perimeters were checked to verify that they were clean and smooth. A $\frac{3}{8}"$ hole was drilled through the appropriate corner of each window frame. A grommet was installed on the entrance and exit holes to prevent chafing of the high voltage and ground wires that passed through these holes. The resulting mess was cleaned up before proceeding further.
5.5 Install and Test the Units

Two rubber 1" x 2" x 1/8" pads were placed on the bottom rail of each frame. The pads served as spacers, and insulated the glass from high-frequency mechanical vibration through the frame. Each unit was lifted up to the level of the frame. The bottom of the unit was first placed on top of the rubber pads, and then the top of the unit was rotated toward the frame until the top was about one foot from the opening. At this point, the high voltage and ground wires were threaded through the hole and the grommet in the frame. The top of the unit was then pushed into position.

The operation of each unit was now tested. During the first of these tests, a problem was found. The seal around one of the reworked high voltage supply wires was not adequate, and arcing to the grounded frame was observed. The sealant on each unit was again cut away and replaced with new sealant. The new sealant was wrapped in masking tape to prevent the uncured sealant from making a mess, and we were able to proceed with the installation.

5.6 Apply the Molding

After each unit passed its functional test, the molding around the units needed to be put in place. The molding had been cut, drilled, and painted in advance. It had been anticipated that the molding would deform when the fasteners were tightened into position, causing a bulge in the molding that could stress the glass. To avoid this potential problem, the holes were cold-worked using a hammer and wide center punch. Also, black tape was placed on the inside surface of the molding to avoid metal-to-glass contact.

The hole locations on the frame were marked. Our initial plan was to simply install the units and use self-tapping screws to secure the molding. Because of clearance considerations, a rather elaborate process for marking and drilling the holes had to be developed.
The hole for each fastener was marked by first placing each unit in its final installed position, then placing the molding around the installed unit. A q-tip was loaded with silver metallic paint from a stamp pad, and then inserted into each pre-drilled hole in the molding.

The molding and unit were removed, the ink dots on the frame were center punched, and pilot holes were drilled. The unit was put back in position, and the molding secured to the frame using #6 x 1\(\frac{1}{4}\)" self-tapping screws. Later, the glass was thoroughly cleaned, and the frame and molding were given a touch up coat of paint.

**5.7 Perform Final Tests**

It had been decided to use an actuation voltage of about 6 kV to ensure a crisp actuation of the slats. As it turned out, this was slightly above the acceptable range, and caused the slats to experience “flutter.” The supply voltage was in the neighborhood of 1.6kV to 1.9kV too high. Tests in the laboratory, confirmed by tests on the final installation, showed that the desired voltage was in the 4.1 to 4.4kV range.

**5.8 Perform Final Electrical Work**

The same electrical contractor who performed the initial set-up also performed the final electrical work. Zener diodes were installed between the high voltage wires and the ground wires to limit the voltage output of the power supplies to the 4.1 to 4.4 kV range. At the suggestion of the power supply manufacturer, all of the electrically conductive material in the electrical junction box was covered with RTV clear silicone gasket maker. This simple step guarded against ionizing the surrounding environment and prevented coronal discharge, also called “spray”.

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After the final electrical work was completed, the units were tested as a group for functional repeatability. Electrical leakage was also tested by listening for coronal discharge.

Interestingly, the installed units opened more reliably than when previously tested in the lab. It was surmised that this was because the installed units used a different type of power supply than was used in the laboratory tests. The arrangement used for the final installation provided a higher current flow during the initial charging of the units, and therefore created a larger transient force to overcome friction.
6 Quality Control

After documenting the part production, assembly, and installation processes, the significant areas of quality control were identified, presented in the following table.

Table 6.1 Significant Quality Controls of the Manufacturing Process

<table>
<thead>
<tr>
<th>Assembly Step</th>
<th>Significant Quality Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Clean and prepare the work area.</td>
<td>Work area cleanliness</td>
</tr>
<tr>
<td></td>
<td>Arrange tools</td>
</tr>
<tr>
<td></td>
<td>Wash hands</td>
</tr>
<tr>
<td>2 Set up the rotating table.</td>
<td>N/A</td>
</tr>
<tr>
<td>3 Assemble the slats, ladders, and tabs.</td>
<td>Cleanliness of slats</td>
</tr>
<tr>
<td></td>
<td>Slats paired in slat racks</td>
</tr>
<tr>
<td></td>
<td>Correct length of slats</td>
</tr>
<tr>
<td></td>
<td>Smoothness of ladder pivots</td>
</tr>
<tr>
<td></td>
<td>Tab quality</td>
</tr>
<tr>
<td></td>
<td>All parts have correct relative orientation</td>
</tr>
<tr>
<td></td>
<td>Ladders deformed as little as possible</td>
</tr>
<tr>
<td>4 Remove the slat racks.</td>
<td>Double check all aspects of tab assembly</td>
</tr>
<tr>
<td>5 Assemble the air spacer.</td>
<td>N/A</td>
</tr>
<tr>
<td>6 Install the air spacer.</td>
<td>N/A</td>
</tr>
<tr>
<td>7 Install the glass.</td>
<td>Cleanliness of glass</td>
</tr>
<tr>
<td></td>
<td>Correct orientation of glass</td>
</tr>
<tr>
<td></td>
<td>Sufficient sealant gap along edges</td>
</tr>
<tr>
<td>8 Perform functional test.</td>
<td>Repeated smooth operation of all slats</td>
</tr>
<tr>
<td></td>
<td>No flutter</td>
</tr>
<tr>
<td></td>
<td>No arcing</td>
</tr>
<tr>
<td>9 Seal the unit.</td>
<td>Air spacer not bowed in</td>
</tr>
<tr>
<td>10 Store the unit.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
7 Conclusions

The most important conclusions from this experience were the most basic. First and foremost, the performance of the powerblind units installed in the Talley Student Center were just shy of perfect, and they continue to perform well. The staff and visitors who use the boardroom on a daily basis have provided us with a great deal of praise and enthusiasm for this affordable, switch-operated adaptive shading solution. The idea appears to be sound.

The following sections list issues and observations that came out of this experience.

7.1 Safety Considerations

The possible effects of electrical discharge have not been investigated. Sooner or later, someone will receive a significant electrical shock. What if that person has special medical problems, which gives them extreme sensitivity to small doses of high voltage current? Could a shock cause a fire, or another hazard? What if volatile, explosive materials are stored near a unit? If a very large square footage of units are connected together, would the hazard be greater, and if so, to what extent?

The amount of mechanical energy used to actuate these windows is quite small, and despite the high voltages, the currents involved are quite tiny. Several research workers have received electric shocks from these appliances (including the author and faculty advisor) without any ill effects other than immediate discomfort. These safety issues, however, have not been examined in a scientific manner, and need to be before large-scale mass production begins.
7.2 Sticking Slats

The powerblinds performed with great consistency - considering the fact that few quality control measures were in place, and students without any prior training performed the work with hand tools. However, several of the slats would “stick” when they were supposed to open. Several slats were too long, an air spacer was bowed in, and a bent ladder caused a tab to rub up against a slat. An absolutely reliable method of production needs to be implemented.

7.3 Non-Operational Bottom Slats

The bottom slats do not open reliably. The reason for this appears to be understood, but a remedy has not yet been implemented.

7.4 Tab Insertion

The tab insertion process was labor intensive, and difficult for some workers to perform. The tab insertion process also required far more time than any other single step. The automation of this step, if possible, is highly recommended. The automation of this step should also reduce the bending of the ladders that occurs during this step.

7.5 Parts Procurement

Presently, student manpower goes into making parts. This part of the production could well be performed by professional job shops, out-of-house, thereby freeing up the students’ time for the other tasks, such as experimentation and assembly.

7.6 Quality Control

Currently, the only instructions or organized measures for quality control are contained in a short document written at the beginning of the assembly phase of the project. Since that time, much has been learned about how to make a quality powerblind. Almost all of the significant quality controls are qualitative rather than quantitative in nature. This area of development is second only to safety in importance. These concerns need to be addressed in order to be able to perform a real evaluation of the reliability of the production process.
7.7 Input Signal Tests

The actuation voltage had a desired specification window. When it was too low, the slats would not open reliably. When it was too high, the slats were observed to flutter. The flutter phenomenon was not well understood. If understood, it could potentially be eliminated. For example, a modification of the circuit that provided an appropriate level of resistive dissipation might eliminate the problem. By eliminating this problem, the tolerances on the supply voltages could increase, simplifying several aspects of the design. Specifically, a remedy to this problem could reduce the cost of the power supplies, or increase the steady-state voltage of the supplies in order to reduce the sensitivity of the slats to friction (to reduce the potential “sticking”). This analysis of this phenomenon represents a potential candidate for a PhD dissertation.

7.8 Electrical Insulation

The insulation of wires that carry static electricity is particularly important because static electricity flows freely on the surfaces of conductors and insulators alike, making it difficult to isolate. Good quality high voltage wires and well insulated electrical connections are very important. This issue needs further attention.

7.9 Mutton and Ladder Discharge

If all of the components do not have sufficient electrical connection, then voltage differences can arise between parts, causing arcing across the air gaps. This was observed at the bottom of the muttons. The long-term effects of this are not known, and needs to be investigated in more detail.
7.10 Shipping

Although the finished units appear to be quite sturdy, we have had little experience with shipping the units. Will they stand up to the loads, and are there special handling requirements that need to be considered? This has not been examined in any detail. When the units were transported to the Student Center, it was with great care in the back of a very slow moving truck for the distance of about 1 mile.

7.11 Coronal Discharge

Approximately 6 months after the installation, small specks of material were noticed on the inside of the low-emissivity glass where none had been previously. The distribution of the material mirrored the edge of a section of a nearby slat. It was theorized that there was a coronal discharge from the edge of that section of that particular slat, which had carried transported tiny amounts of matter from the edge of the slat to the inside of the low-emissivity glass. This represents a potential quality problem that is still being discovered.

7.12 Final Comment

When writing this thesis, the units had not yet been installed in large commercial job. Such a job will surely lead to more learning and more helpful lessons. It will be interesting to keep in touch and follow the progress of the project.
Agarwal, Amit., “A Part and Assembly Process for the Production of the Powerblind.”


