Effective Utilization of Mock-ups Within the Building Envelope Commissioning Process

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ABSTRACT

One aspect most critical to the building envelope commissioning process is mock-up evaluation. To accurately assess the design aspects of any component, assembly, or system prior to installation at site, mock-ups of the key system details should be constructed for review and testing by the commissioning authority for compliance with the owner's performance requirements (OPR), basis of design (BOD), and contract documents. It is critical that each mock-up installation be representative of the performance requirements specified for the project and the quality standard of the future construction. While that concept seems simple, the mock-up phase remains one of the more misunderstood and misapplied processes during building envelope-commissioning, such that the full benefits offered through mock-up evaluation are often not realized.

This paper will examine numerous aspects of the mock-up evaluation as it pertains to the commissioning of building envelope systems, including: how and what to specify, selection of components and assemblies, procedures for constructing, available test methods and procedures, interpreting test results, and resolving performance problems. Additionally, this paper identifies the different types of mock-ups (including the pros and cons of each and how to determine where each is applicable) and the difference between functional and aesthetic mock-ups.

INTRODUCTION

One of the most significant advances in the construction industry over the past several years has been the increased recognition of whole-building commissioning as an effective tool to aid in the assurance of building performance over its expected life cycle. The National Institute of Building Sciences (NIBS) Guideline 3-2006, Exterior Enclosure Technical Requirements for the Commissioning Process, refers to commissioning as "a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria."

Commissioning of a building system can be defined as a systematic process of ensuring that the building system performs interactively according to the designer's design intent and the user's occupational requirements, through verification of the system's performance during the construction period.

Historically, commissioning has been associated with a building's mechanical systems. However, the demand for improved energy efficiency and longer life cycles in today's buildings led to the development and implementation of whole-building commissioning, which specifically focuses on the building envelope. Indeed, with building owners, design professionals, and contractors having a greater awareness of the benefits that a building envelope-commissioning program can provide, it is not surprising that the inclusion of building envelope commissioning in commercial construction project specifications continues to increase in prevalence.

The building envelope-commissioning process commences at BOD and continues through the duration of the project to completion and, in some cases, beyond completion. For simplicity, the tasks comprising the process are often separated into the following phases:

- Predesign
- Design
- Preconstruction
- Construction
- Operations and maintenance (O&M)

The objectives of the building envelope-commissioning process are driven by building type, expected life cycles, geographic location, climatic considerations, desired energy efficiency, budgetary constraints, and tolerance for leakage, all of which may vary considerably among projects. While the precise tasks comprising the commissioning process will differ from project to project, Annex F of the NIBS Guideline 3-2006 contains a fairly comprehensive list of the roles and responsibilities that remain consistent throughout the commissioning process.

To date, the majority of research and development in building envelope commissioning appears to have focused primarily on either the design phase, through drawing and specification review, or the construction phase, by inspection and testing the as-built construction. However, numerous issues that may arise during construction, such as applicator skill level, site conditions, material incompatibilities, scheduling or sequencing conflicts, and confusion or disagreements over testing procedures, can be eliminated through proper commissioning procedures conducted during the preconstruction phase of the project. Specifically, the utilization of mock-ups and the construction, inspection, and testing thereof, can significantly reduce the number of issues encountered during the construction phase.

MOCK-UP OBJECTIVES

Mock-ups are full-sized structural models made with the exact construction techniques, materials, and technicians that will be used on a project, providing the project team (owner, designer, contractors, consultants) with the opportunity to assess a three-dimensional representation of a design and serving as a means to evaluate functionality, determine compliance with project documents, assess aesthetics, establish quality standards, and enhance workmanship. A primary mock-up objective is to address issues prior to construction to minimize disruption to the critical path of construction through the following:

- Verifying that design details will function in accordance with the design intent by determining performance characteristics through functional testing and subsequent comparisons with project requirements;
- Determining whether the installers possess the required skill level necessary to install the components, assemblies, or systems such that the as-built construction will satisfy specified project requirements;
- Providing the opportunity for different trades to experience the sequence of construction and discuss alternative sequencing options;
- Serving as the benchmark for the standard of workmanship and aesthetics to be replicated throughout the project; and
- Affording an opportunity to recog-

Figure 1 – Mock-up constructed at laboratory of Architectural Testing Inc.

Figure 2 – Construction of an on-site, stand-alone mock-up.

nize and resolve potential areas of conflict prior to the commencement of construction.

MOCK-UPS AND THE BUILDING ENVELOPE COMMISSIONING PROCESS

Given the ever-growing importance of schedule, increased performance expectations, the swell of construction litigation, a flood of new construction products, and diminished experience of the tradesmen, it should come as no surprise that mock-ups have become standard practice in most commercial construction projects as a means to evaluate the design aspects of a system or assembly as it is to be installed on site. As mock-up evaluation is an integral part of a complete building envelope commissioning process, it is imperative that the building envelope commissioning agent (BECA) be involved in all stages of the mock-up process, from the design phase through testing and posttest evaluation and troubleshooting. The BECA should assist the designer in specifying the components, details, and assemblies to comprise the mock-ups, as well asfdsa the inspection and testing protocols to which the mock-ups will ultimately be evaluated.

Mock-Up Types

There are four primary mock-up types that can be considered for inclusion on projects:

A. **Off-site laboratory mock-ups –** Full-scale mock-ups constructed, examined, and tested in a laboratory setting under controlled conditions (*Figure 1*),

B. **On-site "stand-alone" mock-ups –** Freestanding mock-ups constructed, examined, and tested at the building site (or at a remote location such as a contractor's facility) that are built separately from the building (*Figure 2*),

C. **Integrated mock-ups –** Mock-ups constructed directly onto

Figure 3 – Integrated mock-up.

Figure 4 – Mini mock-up of air barrier installation.

the building structure where, if deemed compliant to contract documents after evaluation, they become a portion of the final construction (*Figure 3*), and

D. **Mini mock-ups or detail mock-ups** – Small mock-ups for review of details that could not be included in the larger, start-up mock-up (*Figure 4*).

The pros and cons of each of the above types are identified below:

A. Laboratory mock-ups

Pros:

- As the mock-up is evaluated long before construction, issues that arise can be addressed and rectified with minimal impact to the construction schedule.
- Construction and evaluation of the mock-up are performed under controlled conditions.
- It is often more practical to perform certain tests under laboratory conditions as opposed to on site.
- Several conditions that are remote from each other on the actual building can be integrated into a single mock-up.

Cons:

- The transfer of labor and materials to the laboratory may be costly.
- The mock-up is constructed under significant scrutiny such that the level of workmanship may be inadvertently raised compared to the field construction.
- Laboratory mock-ups typically do not address transitions and various field conditions that will involve the coordination of various trades.

B. Stand-alone mock-ups

Pros:

- Mock-up construction is local and, therefore, less costly.
- The mock-up can be constructed prior to the commencement of site construction, so issues that arise can be addressed and rectified with minimal impact upon the construction schedule.
- It is more practical to perform certain tests when the mock-up is freestanding as opposed to a part of the building structure.
- Several conditions that are remote from each other on the actual building can be integrated into a single mock-up.

Cons:

- The laboratory needs to be transferred to site and constructed around the mock-up, making it more difficult to perform certain tests.
- There is less control over the environmental and site conditions, as the mock-up may be exposed to climatic conditions, site security breaches, and damage from adjacent activities.

C. Integrated mock-ups

Pros:

- The up-front cost to the owner is typically less than that of laboratory mock-ups and stand-alone mock-ups of similar assemblies.
- As the mock-up is a part of the final construction, the owner is not paying for the same assembly twice.

- Integrated mock-ups most accurately represent real site conditions and installer capabilities.

Cons:

- It is even more difficult to transfer the laboratory to the site, as working on the building structure may inhibit the practicality of performing certain tests.
- Often, the mock-up is pushed back until after the commencement of building construction, making issues inherent on the already installed work difficult and costly to rectify and disruptive to the critical path of construction.
- If testing damages a portion of the final construction, such as during a structural load test, the warranty on that work will be voided or the affected areas replaced at a cost to the owner.

D. Mini mock-ups

Pros:

- As they are typically a part of the final construction, they provide many of the same benefits as integrated mock-ups.
- Details that were not included as a part of the up-front mock-up but may be prevalent throughout the building (such as the air barrier tie-in at the roof-to-wall junction) can be evaluated.

Cons:

- As they are typically a part of the final construction, they have many of the same weaknesses as integrated mock-ups.
- Typically, only simple, smaller-scale tests are applicable for these mock-ups.

The type and quantity of mock-ups that should be specified will vary from project to project and are dependent upon several factors, including building type, complexity and uniqueness of design details, the building's intended function, life-cycle expectancy, climatic conditions to which the building would be reasonably expected to be exposed, owner's expected level of diligence, budgetary constraints, and cost to repair. Typically, the greater the expected performance level of the building or the greater the complexity of the detailing, the more diligent the preconstruction phase of the commissioning process and, therefore, the more thorough the mock-up requirements.

Figure 5 – Aesthetic mock-up to view appearance of glazing.

To simplify the above, a designer must ask, "What is the basis of design?" If the building is the same as the last hundred built, in the same location and with the same detailing (for example, a big-box store), the only significant variable (and thus the only one being evaluated) is workmanship, as the details and assemblies have already been proven. In this case, a simple on-site mock-up evaluation primarily consisting of visual examination and simple testing would likely suffice. A building with more stringent performance requirements and higher life-cycle expectancy, but with simple detailing and components where feasible, might require greater diligence, such as a more complex stand-alone mock-up with a limited number of mini mock-ups utilized throughout. On a building such as a hospital or laboratory, with complex building systems and details and where the performance requirements are most stringent and the life-cycle expectancy at its highest, a diverse and thorough mock-up protocol would be prudent. This might consist of a complex laboratory mock-up built far in advance of building construction and subjected to meticulous examination/testing, one or more stand-alone or integrated mock-ups of different assemblies or systems, and numerous mini mock-ups of unique details not included in the larger mock-ups.

It is important also to differentiate between aesthetic and functional mock-ups. Quite often, the designer simply wants to assess the building aesthetics and calls for a mock-up to be built to gauge how the completed building will look by viewing the color, shape, alignment, or other visual characteristics of the components comprising the exterior façade. As performance is secondary, these mock-ups are not tested, though they can be visually observed for compliance to contract documents. As an example, an owner might call for a curtain wall mock-up comprising several glazing sections to determine whether the color or shade of the glass appears pleasing (*Figure 5*), without concern at that time as to whether the curtain wall system can effectively perform its required functions. That said, while not its primary purpose, aesthetic mock-ups can provide the project team with an opportunity to observe the sequence of construction and, to a degree, evaluate the function of the details, even in the absence of performance testing.

Figure 7 – On-site air infiltration testing of window-wall mock-up.

Figure 6 – Window-wall "mock-up" that was quite different from the designer's intent.

SPECIFYING THE CONSTRUCTION AND TESTING OF MOCK-UPS

The designer will typically specify the requirement for the construction and testing of mock-ups during the building envelope-commissioning phase. A crucial function of the BECA is to assist the designer in developing a mock-up construction-and-testing protocol that ensures that the intent of the designer's specifications and requisite quality assurance program are achieved. Specific components to be included, the

Figure 8 – Laboratory dynamic water penetration testing of mock-up window-wall section.

number of mock-ups, performance requirements, test parameters, and other requirements specific to a particular component or assembly are included in the corresponding sections of the specifications. It is imperative that the specifications be precise in what is being requested for the mock-up so that there is no misinterpretation of the contractor's responsibilities and so that what is constructed is a reasonable representation of the future work as it is to be installed on site (*Figure 6*).

While mock-up installations can be specified for any component or assembly, when it comes to functional-performance testing of mock-ups of building envelope systems, we are primarily referring to the testing of window/curtain wall assemblies (and other fenestrations) or the opaque wall systems and their ability to perform the four key functions of building envelope performance: control of air movement, control of vapor diffusion, thermal performance, and water management, while withstanding the structural loads under which they can be reasonably expected to be exposed.

ASTM E2099[1] describes procedures and documentation to assist the design team in specifying and evaluating preconstruction laboratory mock-ups of exterior wall systems by addressing mock-up design and construction, evaluation and test result analysis, and procedures for documentation

TEST CRITERION	TEST STANDARD
Airtightness (lab)	ASTM E283, Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
Airtightness (field)	ASTM E783, Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors
Airtightness (field or lab)	ASTM E1186, Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems
Structural integrity	ASTM E330, Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air-Pressure Difference
Static water penetration (field)	ASTM E1105, Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air-Pressure Difference
Static water penetration (lab)	ASTM E331, Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air-Pressure Difference
Dynamic water penetration (field or lab)	AAMA 501.1, Standard Test Method for Water Penetration of Windows, Curtain Walls, and Doors Using Dynamic Pressure
Membrane-to-substrate tensile strength (field or lab)	ASTM D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers
Condensation evaluation (field or lab)	Controlled interior and exterior temperatures on finished interior and exterior wall components to evaluate wall cavity temperatures and locate dewpoint
Interstory drift (field or lab)	AAMA 501.4, Recommended Static Test Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic and Wind-Induced Interstory Drifts
Thermal cycling (field or lab)	AAMA 501.5, Test Method for Thermal Cycling of Exterior Walls
Airtightness (field)	ASTM E783 (modified for opaque wall evaluation), Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors

Table 1 – Test methods commonly utilized in window/curtain wall or opaque wall mock-up testing.

throughout the mock-up process. This standard places an emphasis on the coordination needed between the key parties by providing a protocol for exchange of information between said parties.

On laboratory mock-ups or larger freestanding or integrated mock-ups, it is common to find multiple assemblies, such as window and opaque wall, contained in a single mock-up. This allows for testing not only of multiple assemblies under a single protocol, but also of the interface between the assemblies. In fact, when citing a building envelope mock-up, one is most commonly referring to a mock-up containing both a window unit or curtain wall section and the adjoining opaque wall and its typical components (air barrier, masonry ties, insulation, etc.).

While precise combinations of test methods and sequences can be many, typical testing on a window-to-wall laboratory mock-up includes air infiltration (*Figure 7*), static and dynamic water penetration (*Figure 8*), thermal cycling, condensation resistance, interstory drift, and design load and structural overload tests (typically 1.5 times the design load). Depending on project requirements, additional or different tests may be added to the basic sequence. Air infiltration and the static and dynamic water penetration tests are often repeated upon completion of many of the tests listed above to verify the influence of these tests on the overall performance. For example, a building's thermal movement, caused by heating and cooling the structure, is often simulated on the mock-up, followed by air-infiltration and the static and dynamic water-penetration tests.

Often, additional "visual" tests are incorporated into the test sequence to aid in interpreting the test results. Airtightness "smoke" tests, qualitative testing conducted using a smoke candle in conjunction with pressurization or depressurization of the test enclosure, are often performed in conjunction with quantified air-infiltration testing in order to identify precise air-leakage paths or identify system point failures. Other, simpler tests or tests specific to a particular component such as membrane-to-substrate tensile adhesion or airtightness testing of membrane seams and penetrations, can also be incorporated into the test protocol on large mock-ups to provide additional diligence or to be used as the primary means of performance evaluation on integrated mock-ups and mini mock-ups. Test methods commonly utilized during testing of mock-ups of building envelope components are identified in *Table 1*.

ANALYSIS OF TEST RESULTS

The significance of the involvement of the BECA during the mock-up process becomes most apparent during analysis of failure. In the case of a failure, it is the role of the BECA to assist the designer and contractors in determining the cause of that failure, be it installation, materials, design, or other factors. Assessing the direct cause of failure in a multiassembly mock-up is often difficult, and success of failure analysis relies on the BECA's experience and understanding of the following:

- Material composition, installation, and design of all of the different

assemblies;
- The different diagnostic tools and equipment available, as well as the associated limitations of each; and
- How the interaction of the different assemblies affects overall performance.

The interaction of assemblies is often complex and may be counterintuitive. For example, mock-up test results for Assembly B may be influenced by the presence of Assembly A. Specifically, the presence of Assembly A leads to a failure of Assembly B, where under normal testing parameters, each of the two assemblies would pass if tested independently. Consider a mock-up composed of a curtain-wall section and an adjoining metal-panel wall assembly subjected to air- and water-penetration testing, where the test results show the total air/water infiltration through the curtain-wall system has exceeded the allowable. Is there, in fact, a breach within the curtain-wall system, or are the curtain-wall test results presenting symptoms from a breach within the interface between the assemblies where the air/water infiltration would not be present if the curtain-wall section were tested as a stand-alone system?

While the BECA's involvement in analysis of test failures may be apparent, what may not be as obvious is the need for proper analysis of "positive" test results. In order to pass, the mock-up test results must satisfy the specified performance requirements for the project. But even test results that appear to be compliant to project requirements need to be analyzed to ensure that they are truly representative of system performance. If the concentration of a deficient condition is significantly less on a mock-up than on the intended as-built construction, failures could be observed at site but not on the test mock-up. (*Figure 9*).

Figure 9 – Qualitative airtightness smoke test showing concentration of air leakage over small area on a mock-up where quantitative airtightness-test results indicated a "pass."

This phenomenon was recently observed on a window/wall mock-up for a high-performance laboratory, where the results of airtightness testing conducted in general accordance with ASTM E783, Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors, showed that the measured air-flow rate for both the window (0.011 cfm/ft^2 at 1.20 in water) and opaque wall (0.008 cfm/ft^2 at 0.03 in water) fell within the allowable leakage rates of 0.2 cfm/ft^2 at 1.20 in water and 0.020 cfm/ft^2 at 0.03 in water, respectively. However, qualitative airtightness smoke testing conducted on the sample in general accordance with ASTM E1186, Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems, Method 4.2.6, showed the air infiltration was concentrated at the plenum area above the soffit, an area representing approximately 20% of the opaque-wall sample. In other words, the air infiltration localized to an area representing 20% of the sample was accounting for 40% of the total allowable air leakage for the entire sample area. In this case, the results of the mock-up hinge on the amount of square footage that each assembly is allotted in the mock-up.

On a similar window/wall mock-up, the measured air-flow rate was found to be approximately 80% of the allowable for the test area, signifying a "pass" result. Upon further analysis of the test sample, it was determined that the leakage was occurring at breaches in the seals at masonry tie locations, and that only 16% of the masonry ties in the test sample were leaking. That is, a failure rate of only 16% in one component was accounting for 80% of the allowable air leakage for the whole sample. Hence, the concentration of deficient conditions has a direct correlation with the results of the mock-up testing and the relevance in representing field-installed performance.

LESSONS LEARNED

Ultimately, the desired result from mock-up evaluation is to be able to take a proven assembly or system and replicate its installation onto the building. Lessons learned during mock-up construction and evaluations are transferred to the job site such that mistakes made during the mock-up phase are not repeated during actual site construction. This speaks to several important notions:

- As much as is practically possible, the mock-up must be representative of the site conditions. The mock-up should be constructed by the same personnel who will be erecting the assembly or system on the project, overseen by the key personnel who will be acting as site supervisors during actual construction, and using the same materials, by type and brand, that will be used on the on-site installations.
- Mock-up testing procedures should verify compliance with all of the owner's performance requirements, not just select test procedures that are easy to complete and that have little relevance in simulating actual performance.
- The goal of the mock-up should not simply be to pass, but rather to pass the first time using reasonable construction practices and, in the case of a failure, determine the cause of that failure and adjust the design, materials, and/or installation practices accordingly. Too often, a mock-up fails initial testing and, rather than assessing the cause of failure, the mock-up is simply (in the case of excessive air leakage, for example) "patched up" and retested, with this sequence of events continuing until a pass result is finally achieved. The same flawed practices are then carried over to the site, resulting in installations that do not satisfy project specifications.
- Documentation is a key link in ensuring that lessons learned during the mock-up phase are carried through to actual building construction. ASTM E2099 requires that the contractor provide shop drawings that report all modifications made during the mock-up process for approval by the designer, with all changes clearly noted. What is gradually becoming common practice is for the contractor to develop an assembly manual whereby the specific installation procedures utilized on the mock-up can be accurately repeated on site.

The combination of the growing complexity of building envelope design, increasing numbers of different construction materials, the shrinking of schedules, increasingly stringent performance demands, and the need to construct energy-efficient buildings, has led many building owners, designers, and contractors to adopt building envelope commissioning as a means to ensure that the building envelope is constructed to meet the design intent, expected service life, and code requirements, and to aid in the prevention of complications that otherwise might arise during the construction process. A well-designed and accurately defined preconstruction phase that includes relevant mock-up testing evaluation can be an important tool in the arsenal of the building envelope commissioning process as a means to evaluate the design aspects of a system or assembly as it is to be installed on site.

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BUILDING ENVELOPE KNOWLEDGE ASSESSMENT

Test your knowledge of building envelope consulting with the following questions developed by Donald E. Bush, Sr., RRC, FRCI, PE, chairman of RCI's RRC Examination Development Subcommittee.

Humidity and water pressure can be very important elements that must be addressed during the design phase of building envelope projects.

1. **What is absolute humidity?**
2. **What is humidity ratio?**
3. **What is specific humidity?**
4. **What is relative humidity?**
5. **What is water vapor pressure?**

Answers on page 28

BUILDING ENVELOPE KNOWLEDGE ASSESSMENT

Answers to questions from page 27:

1. **Absolute humidity is the ratio of the mass of water vapor to the total volume of the air sample. In international system units (SI units), absolute humidity is expressed as kg/m³. In in/lb units, it is expressed as lb/ft³.**
2. **Humidity ratio is the ratio of mass of water vapor to the mass of dry air contained in the sample. In SI units, humidity ratio is expressed as grams (g) of water vapor per kilogram (kg) of dry air.**
3. **Specific humidity is the ratio of the mass of water vapor to the total mass of the dry air. In SI units, specific humidity is expressed as kgs of water vapor per kg of dry air.**
4. **Relative humidity is the ratio, at a specific temperature, of the moisture content of the air sample if it were at saturation, and the actual moisture content of the air sample. It is given as a percentage.**
5. **Water vapor pressure is the partial pressure exerted by the vapor at a given temperature, also stated as the component of atmospheric pressure contributed by the presence of water vapor. In in/lb units, vapor pressure is given most frequently in inches of mercury (in Hg). In SI units, it is given in Pascals (Pa).**

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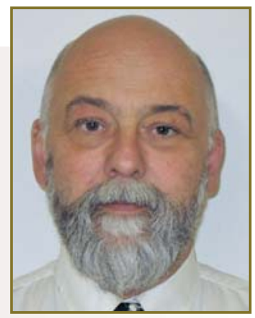
FOOTNOTE

1. At the time of this writing, a standard guide for governing the specification and testing of field exterior wall system mock-ups for fenestration air leakage and static air pressure water penetration resistance was in development by the American Society for Testing and Materials (ASTM).

Kevin D. Knight



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