

# LABORATORY TESTING FOR LOW-SLOPE STANDING SEAM METAL ROOF APPLICATION

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Laboratory testing was performed on a double locked standing seam roof design in a low-slope application. The test project included the design of the test mockups, construction of the test assembly, development of the test procedure, and evaluation of findings from the testing. The intent of the testing program was to assess the resistance of a low-slope standing seam metal roofing system to water leakage after being subjected to thermally induced and/or mechanical movements.

The test specimen or mockup was a 4.0 m x 2.9 m (13 ft 0 in. x 9 ft 7 in.) module of the standing seam metal roof construction, including transverse seams and davits, and incorporating recommendations of both the Sheet Metal and Air Conditioning Contractors National Association (SMACNA) publication and *Copper and Common Sense* regarding low-slope conditions, as well as other industry guidelines. The test apparatus was designed to mechanically cycle the roofing system to simulate the effects of thermal expansion and contraction at transverse and standing seams as required by the design and installation logistics. The mockup was ultimately tested to simulate a 20-year exposure to thermal cycling. Both water spray (in accordance with ASTM E 331) and flood testing were performed to determine the watertightness of the roofing system before and after testing. Based upon results of the different phases of testing, revisions and modifications were made to the system and subsequently evaluated. Design considerations based upon the testing were evaluated.

## KEYWORDS

Flood testing, roofing mockup testing, standing seam metal roofing, thermal expansion/contraction, water leakage, water penetration testing.

## INTRODUCTION

A design team for a long slender building located in a northern region of the United States had designed a standing seam metal roof to provide a durable, attractive enclosure for the structure. Due to the shape and size of the building, the metal roofing system design could not accommodate the industry-recommended guidelines for slope. This situation raised concerns about the watertightness of the roofing system design, especially because panels were to run the length of the building and multiple lengths of relatively long spans were needed. These long panel lengths were expected to undergo large movements during temperature changes and these movements could affect the durability and performance of the roof. In order to evaluate the resistance of the roofing system to water penetration, a testing program was undertaken to determine the effects of thermal movement

and other conditions on the susceptibility of the design to water leakage.

## DESCRIPTION OF ROOFING SYSTEM

The roof section under consideration measured approximately 107 m (350 ft.) long x 18 m (60 ft.) wide and its slope had a curvilinear profile with a radius of approximately 805 m (2,640 ft.). Two parallel rows of continuous skylights, 2.1 m (7 ft. 0 in.) wide and approximately 5.5 mm (18 ft.) apart, ran the entire length of the roof section. Davits supporting a track for an automated window washing system also interrupted the roof adjacent to the skylights. The proposed roofing system for the building (from interior to exterior) consisted of a metal decking system, 76-mm (3-in.) rigid foam insulation, 19-mm (¾-in.) fire-retardant-treated plywood, a self-adhering modified bitumen membrane (SAM) fully adhered to the plywood deck, rosin-sized paper, and 28-gauge terne-coated steel (TCS) standing seam roofing panels measuring 8 m (26 ft.) in length x 305 mm (12 in.) in width.

The plywood was attached to the metal deck with steel screws and plates anchored through the plywood and insulation. The SAM and the rosin-sized paper were continuous below the standing seam panels. The metal roof was attached to the plywood with 50-mm- (2-in.-) wide TCS cleats at 305 mm (12 in.) on center. The vertical standing seams of adjacent panels were coupled together in a double-lock folding process to create 25-mm- (1-in.-) high ribs with the direction of the standing seams or ribs parallel with the direction of the curvature and slope of the roof.

## POTENTIAL ROOFING PROBLEMS AND CONCERNS

Because the radius of curvature for the roof was extremely large, the slope of this roof section was very shallow, especially adjacent to the peak of the roof structure. At the peak of this roof (midpoint of the chord, defining the shape of the building), the slope is zero, and as the roof continues downward, the slope increases to approximately 1:12 (8 percent) at each end of this section of the roof. In the SMACNA Architectural Sheet Metal Manual,<sup>1</sup> standing seam metal roofs are only recommended for roof slopes greater than 3:12 (25 percent), unless special considerations are used for fabrication of the standing seams and lap joints.

Low-slope metal roofing systems can exhibit water leakage problems during heavy, short duration rains as a thick sheet of water develops on the surface of the panels. The thickness of this sheet will depend on the rate of rainfall as well as the surface characteristics and slope of the roof. The volume of water contributing to this sheet development depends not only on the surface area of the roofing panels, but also on

adjacent components. As snow melts, water can also pond on the surface of the standing seams and transverse seams as ice blockage develops. Wind driven rain is an additional factor to be considered.

According to the SMACNA Manual, a standing seam roof that has a slope of 3:12 (25 percent) or less is deemed a low-pitched roof. Low-pitched roofs are unable to shed water quickly. For this reason, SMACNA recommends special detailing that includes applying sealant to the standing seams or increasing the standing seam height at low-pitch areas. When sealant is not used in these low-slope roofing conditions, SMACNA recommends that verification of the roof system design be made to ensure that water will not flood any seam or joint. These SMACNA recommendations primarily deal with the treatment of the vertical standing seams of the roof system, however, and not the transverse seams.

The Revere Copper Products, Inc. publication, *Copper and Common Sense*,<sup>2</sup> discusses other techniques for the prevention of water penetration through seams and joints in low-slope roof areas. This publication states that the transverse seam laps should be increased to 102 mm (4 in.) when the roof slope is between 3:12 and 6:12 (25 percent and 50 percent) to guard against water flowing under the lapped area. In addition to increasing the lap length to 102 mm (4 in.), it also recommends that a bead of sealant should be installed in the lock formed by the soldered locking strip. The lap of the vertical leg of the standing seam in the transverse seam lap should also be set in sealant. *Copper and Common Sense* further states that for standing-seam roofs with slopes that are less than 3:12 (25 percent), a high-grade butyl sealant tape, or alternately a bead of comparable sealant, should be applied to the top flange of the shorter standing-seam leg. This latter recommendation is similar to SMACNA's recommendation. The SMACNA manual does not state how to detail transverse seams in these cases.

Due to the 107-m (350-ft.) length of the structure, movement of the roofing panels due to thermal expansion and contraction was a concern. Many individual lengths of metal panels were required to complete the span due to the intended method of their field fabrication. The 8-m.- (26-ft.-) long metal panels were overlapped to form a series of shingled roof panels that extend the entire length of the roof and each overlap condition created a transverse seam lap joint. These transverse seams are also a potential source for water penetration when the slope is shallow (less than 1:12 [8 percent]) because large cyclical thermal movements can affect any applied seals. In addition, the geometry of the standing seams creates hydrostatic head conditions and sealant configurations that may not be durable. Large thermal expansion of the panels around davits also creates difficult water-proofing problems because the davits on the roof system remain stationary while the panels move around them. Finally, these panel movements can cause sealant problems at panel cleats that are folded into the double-lock folded vertical seams, as these cleats also remain stationary while the panels move over them.

In summary, the potential problems investigated in this study were as follows:

1. Potential water leakage through vertical seams, transverse seams, and davit flashings during heavy rains that create a sheet of water on the surface of the panels as water flows across them.

2. Potential water leakage through vertical seams and transverse seams and davit flashings during rains in combination with periodic wind uplift loads.
3. The effect of thermal movements on the resistance of vertical seams, transverse seams, and davit flashings on water leakage during heavy rains and rains with periodic wind uplift loads.

## MODELING DRAINAGE FLOW OVER THE ROOF SURFACE

In order to determine the thickness of a water sheet that could develop during heavy short duration rains, weather data for the area was examined. Using rainfall data obtained from the United States Department of Commerce for the region, water accumulation was calculated for 2-, 5-, 10-, 25-, 50- and 100- year storm return periods having a 5- or 10-minute storm duration. For a 100-year storm of a 5-minute duration, the rate of water accumulation is about 248 mm (9.8 in.) per hour. For a storm of a 10-minute duration, the rate of water accumulation is about 191 mm (7.5 in.) per hour. The values for rates of water accumulation decrease as the storm return period is shortened. For a two-year storm of a 5-minute duration, the rate at which water will accumulate is about 131 mm (5.2 in.) per hour. For a storm of a 10-minute duration, the rate at which water will accumulate is 101 mm (4.0 in.) per hour.

Using the value obtained for a 100-year storm mean recurrence interval with a 10-minute duration, an analysis of the drainage flow characteristics in the low-slope areas was performed. Two roof conditions were analyzed. The first condition consisted of increasing the quantity of water on the curved roofing panel adjacent to the skylight where water runs off the skylights and onto this roofing panel. The second condition consisted of a single panel in the center of the roof, accommodating only storm water.

The analysis considered the drainage flow over the curved roof by dividing the roof into 20 sections of varying slope and using standard hydraulic flow formulas to evaluate the cumulative effects. Calculations revealed that the maximum amount of rainfall that would accumulate in the panel adjacent to the skylight would not exceed 17.5 mm (0.69 in.) of water flow. The maximum amount of rainfall that would accumulate on the typical field panel would not exceed 7.7 mm (0.30 in.) of water flow at the center of the roof.

The flood test portion of the test program was designed to simulate the effects of the sheet of water that develops during heavy, short duration rains. The mockup was flooded for a period of 24 hours to a height of 25 mm (1 in.) above the base of the pans. Though the height of 25 mm (1 in.) does exceed the calculated values previously discussed, this value was selected to offset erection tolerances existing on the actual mockup and still have at least 23 mm (0.90 in.) of water.

## MODELING THE EFFECTS OF RAIN DURING PERIODIC WIND UPLIFT LOADS

In order to determine the design wind pressures, weather data from the regional airport near the project was examined, as well as data obtained from wind tunnel studies performed by Rowen, Williams, Davis, and Irwin, Inc. A negative uniform static air pressure difference of 814 Pa (17 psf) (in the uplift direction) is the one-year recurrence interval for

the maximum wind gusts experienced at the regional airport and correlates with the wind tunnel studies. This analysis was performed to determine whether positive wind load conditions would ever exist for this roof. A positive wind load condition would drive water into the roofing system, whereas negative pressure would likely reduce penetration. The wind tunnel study revealed that a roof system would never be subjected to a positive wind load condition. The authors used a one-year recurrence interval to simulate a condition that would occur often during the life of the building.

To evaluate the capability of the roofing design to handle the thermal and uplift movements and drainage conditions, a mockup of the standing seam roofing system was designed and a test program was developed. In order to determine the mockup design, the appropriate tests had to be identified and the testing format developed.

The water spray testing portion of the test program was designed to simulate wind-driven rains. This was accomplished by utilizing the water spray rack specified by the American Society for Testing and Materials (ASTM) Standard E 331.<sup>3</sup> This test is similar to ASTM Standard E 1646<sup>4</sup> for water testing metal roofs, which was issued after the completion of this testing program. The water test was used to determine the resistance of the roof system to water penetration at room temperature. The roofing system was tested both with and without a uniform static air pressure difference to simulate the effects of wind. The test specimens were exposed to uniform static air pressure differentials of 0 Pa and -814 Pa (0 psf and -17 psf) (wind uplift) applied in a manner to simulate a gusting (fastest mile or minute) condition on the roof. Water was applied to the exterior surface of the roofing system by means of a grid of water nozzles set to deliver a uniform spray to the entire surface equivalent to a minimum of 5.25 mL/s (5.0 U.S. gallons/sq ft/hour) or an 203 mm (8 in.)/hour rainfall. The 10-minute storm duration rate for a 100-year storm return period is 191 mm (7.5 in.) per hour and compares closely to the rate of water application during the ASTM E 331 water spray test, thus not requiring any changes to this standard procedure. Also, considering the shape of the building, the roofing application, and the wind tunnel studies, the development of significant positive wind loadings on the roof during wind-driven rains was not expected and, therefore, the mockup was not exposed to these conditions. It was assumed that this cycle would only be encountered once per year. At the conclusion of the testing, the authors performed a static load test of -34 psf. This represents the maximum wind load in a 100-year recurrence interval. We observed no permanent deformation of the panels after this testing that would indicate that the waterproofing integrity of the system was not affected.

### MODELING THERMAL MOVEMENTS ACROSS TRANSVERSE JOINTS

The effects of thermal cycling over a 20-year period were simulated to evaluate the adequacy and durability of the roofing system to resist water leakage after exposure to cyclic movement. A test apparatus was designed to mechanically simulate the effects of both thermal expansion and contraction at the transverse and standing seams by subjecting the mockup of the roofing system to longitudinal movement (parallel to the direction of the standing seams). It was assumed that approximately one-half of the days per year in

the Midwest region receive sufficient solar radiation to subject the panels to a 27°C (80°F) temperature differential during the course of the day. It was assumed that the roof system is likely to experience 200 diurnal swings of this magnitude per year. The annual temperature extremes were based on temperature extremes of 71°C (160°F) for a bright summer day and -23°C (-10°F) for an overcast winter day.

The transverse seams were cycled to obtain a movement displacement of 4.8 mm (% in.). This displacement represents one 27°C (80°F) diurnal temperature cycle. Because the diurnal temperature cycles occur over different temperature ranges during the various seasons of the year, the neutral position or center of translation of the test apparatus was changed to achieve a total lap joint displacement or a total transverse seam displacement of 9.5 mm (% in.) (refer to Figure 1). The total displacement of 9.5 mm (% in.) represents the amount of movement that would be experienced during one annual thermal cycle. Both displacement values were based on the following:

$$\begin{aligned} \% \text{ in.} &= 80^{\circ}\text{F} (26 \text{ ft}) (12 \text{ in./ft}) (6.7 \times 10^{-6} \text{ in./}^{\circ}\text{F/ft}) \\ 4.8 \text{ mm} &= 44^{\circ}\text{C} (8 \text{ m}) (103 \text{ mm/m}) (12.1 \times 10^{-6} \text{ mm/}^{\circ}\text{C/m}) \\ \% \text{ in.} &= 170^{\circ}\text{F} (26 \text{ ft}) (12 \text{ in./ft}) (6.7 \times 10^{-6} \text{ in./}^{\circ}\text{F/ft}) \\ 9.5 \text{ mm} &= 94^{\circ}\text{C} (8 \text{ m}) (103 \text{ mm/m}) (12.1 \times 10^{-6} \text{ mm/}^{\circ}\text{C/m}) \end{aligned}$$

The mockup was also subjected to temperature extremes to expose the sealant in the various joints to elevated or lowered temperature conditions. Cooling was accomplished with a combination of refrigeration equipment and dry ice. Heating was accomplished with air heaters and heat lamps.

### ROOFING SYSTEM MOCKUP

The mockup design simulated the roof design and included the same curb height limits, davits, gutters/drains and materials as the actual roofing system. The configuration also incorporated the refinements recommended in both the SMACNA publication and the *Copper and Common Sense* for low-slope conditions. Additional modifications, such as extending the transverse seam lap from 102 mm to 305 mm (4 in. to 12 in.), were incorporated into the mockup to further enhance the watertightness of the system.

Overall dimensions were 4.0 m x 2.9 m (13 ft 0 in. x 9 ft 7 in.). The mockup roof system was attached to a plywood deck over wood joists at approximately 305 mm (12 in.) on center. One side of the chamber deck was constructed with solid plywood, and the other side was constructed with

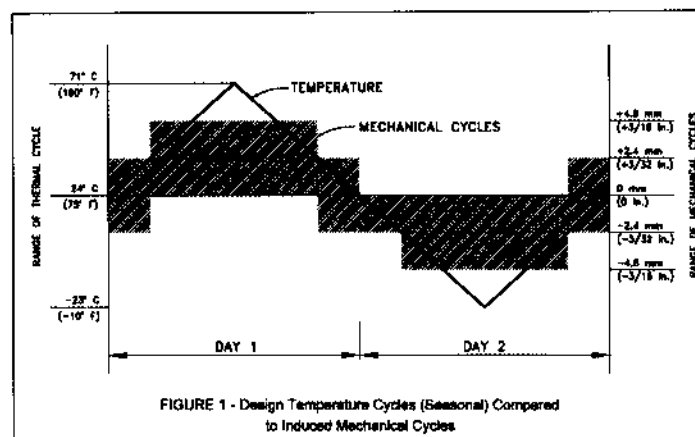


FIGURE 1 - Design Temperature Cycles (Seasonal) Compared to Induced Mechanical Cycles

Figure 1.

102-mm- (4-in.-) wide strips of plywood at 305 mm (12 in.) on center to allow for visual observation of the underside of the roof system. The window washing davits were constructed of steel tubes bolted to wood blocking between the roof joists. The side walls of the test chamber were constructed of wood studs and plywood (refer to Figure 2).

The top enclosure of the test chamber was constructed with wood framing members. Small plexiglass windows were placed in the walls of the enclosure to allow for visual observation of the roof system during the testing. The air pressurization equipment was connected to a 102-mm (4-in.) poly(vinyl) chloride tube located in the center of the enclosure, and a pressure tap was provided for connection of a water manometer, the device used to measure the pressure differences. The water spray grid was suspended from the inside ceiling of the top enclosure.

A steel reaction frame was designed to resist the load required to mechanically cycle the metal panels and induce differential movement at the transverse seams. The load was generated from an MTS dynamic machine, a servo-controlled hydraulic actuator capable of delivering either tension or compression with a maximum throw of 102 mm (4 in.) and adjusted to electronically monitor and control deflection. The load is applied to one side of the roof system via a lever arm that is connected to the MTS machine and a steel tube with four rectangular rods that are attached to a continuous plate secured to the underside of the roof panels. Small plates were placed on the top surface of the roof panels and secured to the continuous plate with two bolts through each standing seam panel. The bolts were tightened to create a friction connection allowing zero slippage of the standing seam roof at the connection. Three triangular steel trusses were constructed at the opposite end of the roof system to form the fixed connection of the reaction frame. The opposing end of the standing seam roof was attached to the trusses with a continuous plate in a similar manner. The entire test chamber and steel reaction frame were bolted into the concrete floor (refer to Figure 3).

The TCS standing seam panels were installed according to proposed details by highly skilled workmen employed by a nationally recognized roofing contractor. The mockup was constructed with eight full-width standing seam panels, each containing a complete transverse seam detail. On both sides of the mockup, small half panels were constructed with a transverse seam that folded up the curb on each side. The

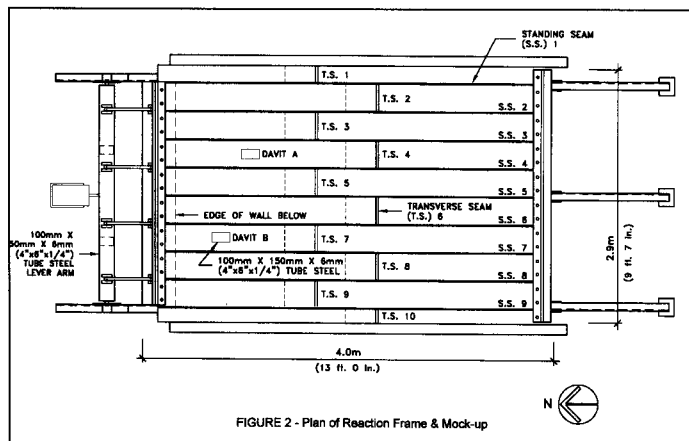


Figure 2.

sequence for installation of the TCS panels was as follows:

1. SAM was placed over the entire surface of plywood deck including the 102-mm- (4-in.-) wide plywood strips used for inspection openings. The window washing davits were also flashed with SAM.
2. Water-indicating paper strips were installed at approximately 152 mm (6 in.) on center to detect any water penetration through the metal roof.
3. Rosin-sized paper was installed in 305-mm- (12-in.-) wide strips between the panel cleats.
4. TCS panels 305 mm (12 in.) wide were laid over the rosin paper. The panels were held down with cleats at 305 mm (12 in.) on center. Each cleat was set on the SAM in a bed of liquid membrane (trowel grade modified asphalt compatible with SAM and nailed to the deck with two nails. The nail holes were covered with butyl sealant and the bottom leg of the cleat folded over the sealed nail heads (refer to Figure 4).
5. To simulate field installation of the panels around the davits, the standing seam panel on the mockup was cut oversized to fit around the davit. A prefabricated metal flashing assembly with upturned legs was placed over the davit and soldered to the standing seam panels. The davits are fixed in place. Panel movement around the davits was

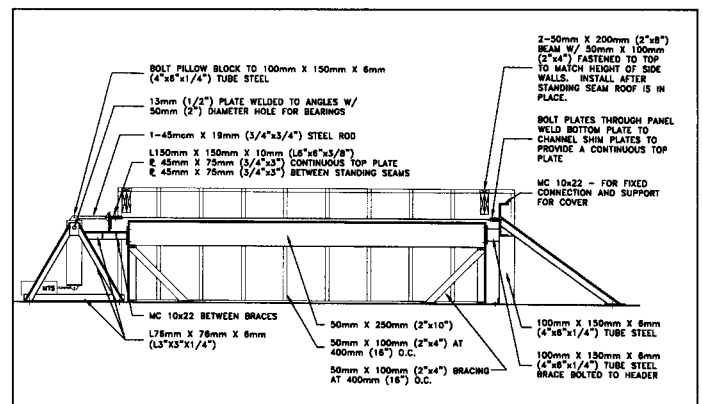


Figure 3.

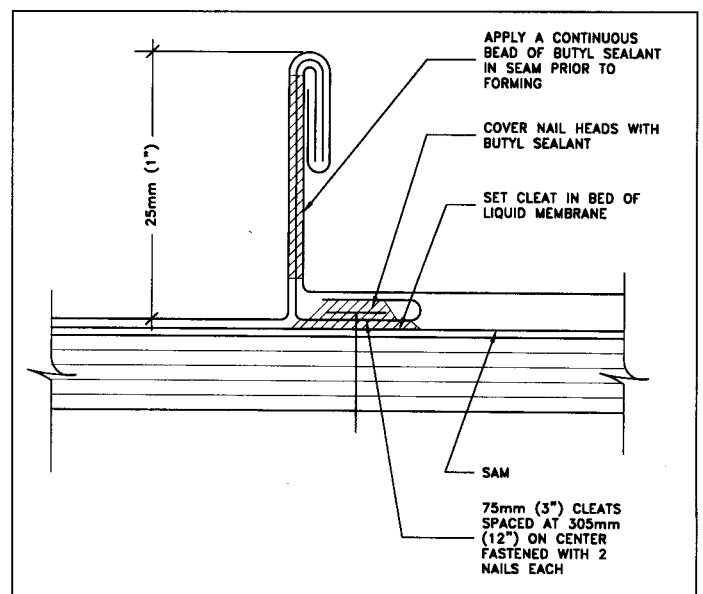


Figure 4

accommodated by the oversized opening in the panel and the flexibility of a lead boot flashing.

6. A specially designed two-piece lead boot davit flashing was soldered to the horizontal portion of the TCS panel. A metal drawband strap was used to attach the flashing to the davit. A bead of butyl sealant was placed over the top edge of the lead flashing to seal the joint.
7. A continuous bead of butyl sealant was placed inside the vertical legs before the fold of the standing seam was formed.
8. A bead of sealant was placed inside the 19-mm ( $\frac{3}{4}$  in.) hemmed edge used to attach the panels to the continuous transverse seam cleat.
9. Once all the panels were installed, the seams were folded together in a double-lock standing seam by hand or by the use of a mechanical seam roller. Amounts of the butyl sealant applied inside the standing seam extruded from the folds during forming and was cleaned from the surface of the metal.
10. The exposed transverse seams were sealed using a 19-mm ( $\frac{3}{4}$  in.) bond breaker tape over the seam joints and applying a 6-mm x 50-mm ( $\frac{1}{4}$  in. x 2 in.) bead of silicone sealant over the bond breaker tape (refer to Figure 5).

## OVERVIEW OF TESTING PROGRAM

The testing program evolved into three phases. Observations regarding each of these phases are described in detail in the following section. In the first phase, the apparatus for mechanical cycling and the equipment for evaluating the roof system response to water were refined. Initially, this mockup was to be used to conduct the complete testing program; however, leaks developed during the first set of cycles.

In the second phase, several smaller mockups were developed and additional methods of water leakage testing were performed to investigate the causes of the water leakage. These involved some tests where dams were created to pond water in isolated areas.

In the third phase, a new mockup was built that incorporated many of the modifications to the testing apparatus and to the roofing system design that were developed during Phases 1 and 2.

### Phase 1

The Phase 1 testing consisted of the following:

1. Perform 1,000 mechanical cycles between 71°C and -23°C (160°F and -10°F).
2. Perform 15-minute water spray test per ASTM E 331 with five air pressure spikes for 0 Pa and -814 Pa (0 to -17 psf).

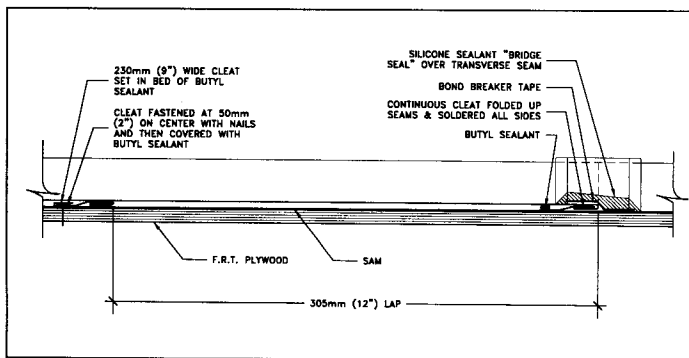


Figure 5.

3. Perform 24-hour flood test at 25-mm (1-in.) level.

### Phase 2

The Phase 2 testing consisted of the following:

1. Flood test transverse seams by using water stops to isolate them. The isolated locations were filled with water to the top of the transverse seam sealant.
2. Flood test north half of mockup with 13 mm ( $\frac{1}{2}$  in.) water after isolating the north half of mockup from south half, and also isolating the davits and transverse seams.
3. Flood test isolated north half of mockup to 25 mm (1 in.) water.
4. Flood test isolated regions around davits to 25 mm (1 in.) water.
5. Flood test south half of mockup with 25 mm (1 in.) water.
6. Unfold standing seams and inspect cleats. Install butyl sealant directly under the panel cleat and refold the standing seams.
7. Flood test mockup after refolding seams to 25 mm (1 in.) water.
8. Concurrently with the flood test in item No. 7, build a separate mockup, the same size, but with no transverse seams included in the construction. Seal all of the standing seams with butyl sealant.
9. Flood test mockup with no transverse seams to 25 mm (1 in.) water for a three-day period.

### Phase 3

The Phase 3 testing consisted of the following:

1. Remove original mockup as described for Phases 1 and 2 and construct a new mockup incorporating modified davit flashing and butyl sealant beneath standing seam panel cleats.
2. Flood test new revised mockup to 25 mm (1 in.) water.
3. Perform 1,000 mechanical cycles.
4. Perform 15-minute water spray test per ASTM E 331 with 5 air pressure spikes from 0 Pa and -814 Pa (0 to -17 psf).
5. Flood test entire mockup to 25 mm (1 in.) water.
6. Perform 3,000 mechanical cycles.
7. Perform 15-minute water spray test per ASTM E 331 with five air pressure spikes from 0 Pa and -814 Pa (0 to -17 psf).
8. Flood test mockup in increments of 3 mm, 19 mm and 25 mm ( $\frac{1}{8}$  in.,  $\frac{3}{4}$  in. and 1 in.) water.

## OBSERVATIONS DURING TESTING

### Observations During Phase 1 Testing

Phase 1 testing began by mechanically cycling the panels. After 1,000 mechanical cycles were completed, the roof mockup was visually examined for evidence of distress caused by the cycling. Two small splits, ranging in size from 3 mm to 6 mm ( $\frac{1}{8}$  in. to  $\frac{1}{4}$  in.), were observed in the transverse seam silicone sealant at one location. The splits occurred on the vertical upturn portion of the sealant along the uppermost edge of the standing seam. However, no water leakage was observed during the ASTM E 331 water spray test when the roof mockup was subjected to water spray in conjunction with static air pressure difference or when the roof was subjected to water spray with and without the application of a static air pressure difference. The testing continued by flooding the roof mockup to the height of the top of the standing seams. Extensive leakage was observed inside beneath the

standing seams when the water was ponded on the surface of the metal roofing panels. These leak locations are shown in Figure 6. The total amount of water that penetrated through the roofing system was not measured due to the volume of leakage. Water entered the roof system through all of the standing seams except one. This seam had been modified by installing silicone sealant along the length of the vertical seam prior to the start of the testing to evaluate its effectiveness in accommodating movement.

### Observations During Phase 2 Testing

Upon completion of the Phase 1 test, when the roof system was flooded, a relationship was observed between the level of water on the roof and the amount of water leakage that occurred. If the water level was maintained below the top of the standing seam, the roof system leaked only slightly and at isolated locations. To identify the leak source in the roof system and to study this relationship, the transverse seams and the davit locations were isolated from the remainder of the roof system with small plexiglass dams and butyl sealant to evaluate specific joints for watertightness.

When the water on the sectioned-off north half of the mockup was flooded to the top of the standing seams, leakage occurred through the metal dam where the metal roof terminates.

Sources of water leakage were attributed to conditions at or around the davit flashings and leakage through the standing seams. Leakage through the standing seams occurred either through the vertical (upturned) portions of the transverse sealant or at panel cleats. Along the standing seam where the panel cleats were fastened, the butyl sealant application in the standing seam was interrupted. The cleats were initially installed dry on the metal panel, and the next panel was installed with butyl sealant placed in the fold. When the panel was laid down over the cleats, the butyl sealant covered only the top of the cleats, leaving the area under the cleats without sealant. Neither the SMACNA publication nor *Copper and Common Sense* discusses sealing of cleats in low-slope roof areas.

Because water penetration through the area around the unsealed cleats could not be eliminated, the mockup was disassembled and modified. Trial repairs to seal the panel cleats were implemented by locating the panel cleats, opening the standing seam folds, placing butyl sealant in the joint under the panel cleat, and folding the seams back into their double-folded position without resulting in any visual distortions.

The roof panels were then flooded again to determine if these trial repairs were effective. With these modifications, water leakage occurred through the metal roof system at approximately the same volume and rate as observed during the previous flood tests of Phase 1, indicating that either the repairs were not effective or that leakage through the transverse seams was significant.

A second trial mockup panel, composed of several continuous metal panels with no transverse seams or davits, was then constructed to evaluate whether the panel cleats could be effectively sealed. The panel cleats were sealed by applying butyl sealant beneath each cleat in addition to the butyl sealant placed within the standing seams. This trial mockup was then flooded with water to the height of the top of the standing seams for three days, with no signs of any leakage through the standing seams. However, no thermal cycling was performed on this system to assess degradation associated with movement.

### Observations During Phase 3 Testing

The original mockup that was installed in Phase 2 was completely rebuilt and included two different davit flashing details. Davit A was fitted with an "L"-shaped water stop 25 mm (1 in.) high soldered to the horizontal portion of the panel around the davit. The two-piece lead boot was then placed over the water stop and installed in the same manner as before. The water stop was installed so that any water that penetrated the solder joints around the lead boot would not penetrate the opening cut in the standing seams for fitting around the davit. At Davit B, a bead of butyl sealant was placed on the inside of the flange of the lead flashing boot. This davit did not contain a water stop. The lead boot was then soldered and installed in the same manner as before. The sealant was intended to act as a water stop to restrict water from entering the opening cut in the panel, should the solder joints around the lead boot fail.

The leak occurred at the west side of Davit A. At this location, the panel was cut through the standing seam to facilitate the installation of the panel around the davit. A TCS "L" water stop had been soldered around the davit before the lead boot was soldered to the panel; however, the leakage appeared to be coming from the standing seam area.

The test procedure continued as planned to determine if any new leaks became apparent after testing. Phase 3 Part 2, testing of the revised mockup roof system began with the in-phase simulated five-year exposure consisting of 1,000 mechanical cycles. No noticeable leakage occurred during this first phase of testing. Additionally, no water leakage was observed during the Phase 3, Part 3-ASTM E 331 water spray test, and no leakage was observed when the mockup roof system was subjected to both zero pressure and negative pressure.

Testing proceeded with Phase 3, Part 4-flood test, during which the roof mockup was flooded to the height of the top of the standing seams. Considerable leakage occurred through the roof system during this portion of the test. Leakage occurred at the two initial leak locations and three new leak locations.

The source of the initial two leaks and the three new leaks that developed after the first 1,000 cycles of the revised test program was investigated. (Leak locations are shown in Figure 7.) Leak No. 1 was attributed to either a sealant void in the standing seam or leakage at the top portion of the transverse sealant. The leakage occurred along the seam and

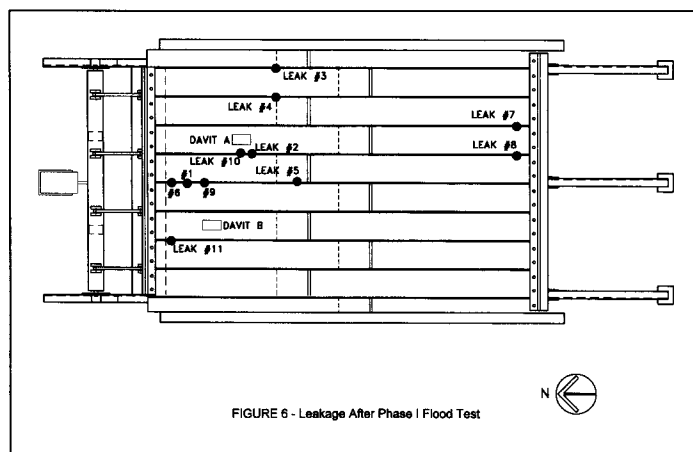


FIGURE 6 - Leakage After Phase 1 Flood Test

Figure 6.

water migrated along the seam and out the end of the test chamber.

Leak No. 2 occurred at Davit A. This area was repeatedly tested by creating small dams of butyl sealant and testing selected areas. The rate of leakage resulting from testing at these smaller isolated areas never equalled the rate observed during the full-scale flood test. Two plexiglass dams were created on either side of the davit between the standing seams. Once the entire area around the davit was flooded, the rate of leakage was approximately the same as that recorded during the flood test. The source of this leak could not be definitively identified without completely dismantling the roof system. However, it appeared to be associated with the standing seam in this area. The solder joints around the cut portion of the roof panel that fit around the davits were damaged when the standing seams were folded.

Leaks No. 3 and 4 were the result of water entering the transverse seam at the point where the transverse seam sealant turned up the standing seam fold. At this location, a shearing action took place in the sealant, resulting in the sealant becoming debonded from the surface of the metal. Water penetrated the sealant at this location and filled the transverse seam lap joint.

Sealant at the vertical upturn was inspected at the remaining transverse seams. Hand pressure applied to the horizontal portion of the transverse seam and to the 305-mm (12-in.) lap resulted in water being pumped out at the bottom edge of the standing seam fold adjacent to the vertical upturn of the sealant. Water flowed out from six of the eight transverse seams at the vertical upturn of the sealant. Water that entered the other transverse seams did not leak since water needed to build up over the height of the back hemmed edge before it could be observed below the mockup.

Leak No. 5 was located at Davit B. The same procedure was utilized for isolating the leak at Davit A. As the leak was being isolated, cracks were observed in the solder joints around the lead flashing boot. These cracks were soldered tight, the area was flood tested again, and no leakage occurred. The cracks in the solder joints were likely the result of fatigue from the mechanical cycling.

Four thousand additional mechanical cycles were performed for a total of 5,000 cycles at room temperature. The additional 4,000 mechanical cycles were performed to evaluate the durability of the system to accommodate movement for an expected twenty-year period. The amount of movement at the transverse seam was approximately 5 mm ( $\frac{1}{4}$  in.).

The center point of the cycle was shifted similar to the hot and cold temperature shifts after 2,000, 3,000, and 4,000 cycles to maintain the total overall movement of 10 mm ( $\frac{1}{2}$  in.) during annual cycles.

As the system was mechanically cycled, the butyl sealant placed in the standing seams extruded out of the folds of the seams at the location where the panels were staggered. At this location, one panel moved relative to the fixed adjacent panel, causing the butyl sealant to be pushed out the folds of the standing seam. This resulted in voids in the butyl sealant, creating a situation where water could enter the standing seam. During the mechanical cycles, the flashings at both davits appeared to slide back and forth with the movement of the panels, resulting in an opening in the butyl sealant around the top of the lead flashing. The metal drawband used to fasten the lead boot to the davit was not a snug fit, allowing the flashing to slide back and forth. The davit flashing rocked back and forth in a pendulum-type motion rather than side to side.

Only flood tests were performed on the mockup in conjunction with this series of cycles because the gaps at the davits would have likely produced a leak under water spray testing. A flood test was performed at the end of 2,000 cycles and 5,000 cycles.

The flood test after the completion of 2,000 mechanical cycles (Phase 3) resulted in eight leaks in the roof system. (Leak locations are indicated in Figure 8.) Leaks No. 1, 2, and 4 occurred at the same locations as noted during the previous test. Leak No. 3 was located at the inspection opening from the previous test made in the first full transverse seam, indicating that leakage occurred through the transverse seam sealant at the vertical upturn.

Intense leakage occurred immediately at Davit B (Leak No. 5) when the mockup was flooded. Water leakage, at a rate of approximately 1.05 mL/s (1 gallon per hour), was collected at the 102-mm- (4-in.-) diameter inspection hole near the davit. The source of the leakage was the hairline fractures in the solder joints.

Leak No. 6 was only a slight drip and occurred either at the fixed edge of the transverse seam lap or a panel cleat that was located in the area. Leak No. 7 was associated with a cleat directly over the slight drip. Leak No. 8 occurred at the far west inspection hole drilled into the solid portion of the deck. The source of this leak was not definitively determined, but was most likely the result of excess water on the roof deck.

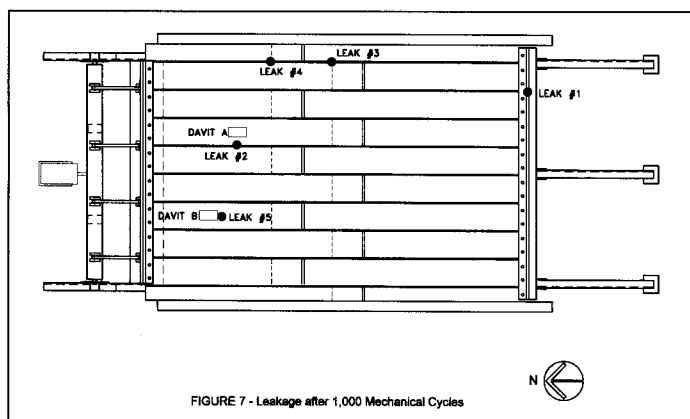


FIGURE 7 - Leakage after 1,000 Mechanical Cycles

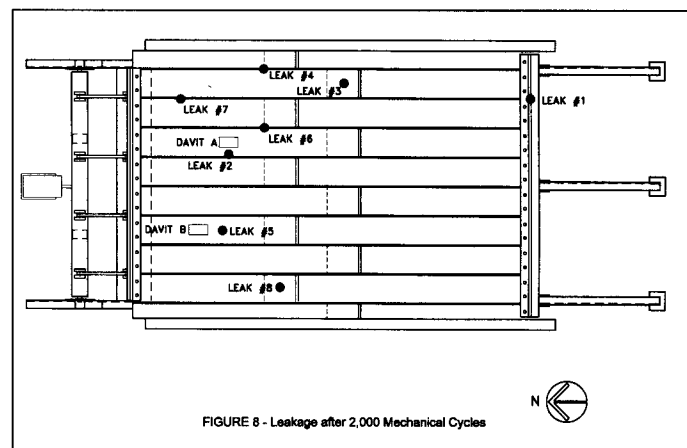


FIGURE 8 - Leakage after 2,000 Mechanical Cycles

Figure 7.

Figure 8.



The roof system was flood tested after the completion of the 5,000 mechanical cycles (Phase 3) in three steps. The leak locations from this test are shown in Figure 9. The davits were isolated from the roof with small plexiglass dams to determine the height of water at which leakage occurred. Water was filled to one-half the height of the standing seam with no signs of leakage through the davit areas. The water level was raised to three-quarters the seam height with no leakage observed around the Davit A; however, there was significant leakage at Davit B (Leak No. 5). Fractures occurred in the solder joints around the davit, resulting from the rocking motion. These fractures were covered with butyl sealant and the areas around both davits were filled with water to the top of the standing seam. No further leakage was observed at Davit B; however, a small leak developed at Davit A (Leak No. 2). Although this leak occurred at the same location as noted previously, the rate of leakage was significantly less. Based upon these leaks, it was concluded that standing seams were contributing to leakage.

The remainder of the roof mockup was then flooded to approximately one-half the standing-seam height. No new leakage was observed. Additionally, there was no evidence of new water leakage when the mockup was flooded with approximately 19 mm ( $\frac{3}{4}$  in.) of water. However, once the roof mockup was flooded to the top of the standing seams at approximately 25 mm (1 in.), six new leaks developed. A few of the leaks (Nos. 1, 2, 3, 5, 6 and 8) occurred at the same location as previously noted under Phase 2; some previous leaks (Nos. 4 and 7) had disappeared; and some new leak locations (now identified as Nos. 4 and 7) developed.

Leak No. 8 occurred at a transverse seam. Since the roof deck was previously dry and the Davit B flashing leak did not cause water to flow across the deck, this leak was attributed to water leaking through the vertical upturn of the transverse seam sealant. A new leak (Leak No. 7) developed at the side of Davit A, resulting from a cleat directly over the leak. The source of Leak No. 4 was most likely the vertical upturn in the transverse seam sealant similar to Leak No. 8 described above.

The leak previously identified as Leak No. 4 under the Phase 1 and Phase 3, Part 2 testing disappeared. This leak had been attributed to a vertical upturn of the transverse seam sealant. However, the source of this leak was likely the result of a cleat in the nearby area. The butyl sealant located within the folds of the standing seam probably separated from the adjacent metal, resulting in the earlier leakage.

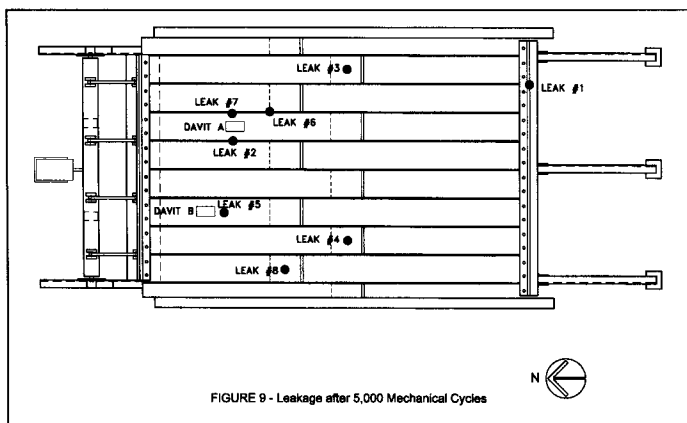


Figure 9.

With the additional mechanical cycles and the nature of butyl sealant to remain gummy, the sealant most likely healed itself, thus closing off the source of the leakage.

Three modes of failure were identified in the Phase 3 tests: leakage at davits, leakage through standing seams, and leakage through the vertical upturn of the transverse seam. Leakage occurred at both davit locations, either through the panel splice or from the davit flashing itself. Three leaks could be attributed to the vertical upturn of the transverse seam. Three leaks were also attributed to butyl sealant failing at the panel cleats. Finally, two leaks were attributed to either the vertical upturn of the transverse seam or to a panel cleat (refer to Figure 10).

## SUMMARY OF TEST RESULTS

Observations made during the testing program and an analysis of the conditions encountered revealed the following results of the testing program:

1. The horizontal portion of the transverse seam sealant performed satisfactorily during all testing phases.
2. No leakage was observed through the SAM membrane during the testing.
3. Three leaks were observed at panel cleats when ponded with 25 mm (1 in.) of water indicating that water can penetrate the seam, travel longitudinally in the fold of the standing seam, and leak outside the test frame. Movement of the standing seam panels relative to the cleats can cause a wearing action such that the butyl sealant is pushed from the surface of the metal creating a small void in the sealant.
4. Butyl sealant within the standing seam was extruded from the seam when the folds were formed and during the mechanical cycling, resulting in isolated voids in the sealant.
5. Sealant must be placed below the cleats to prevent leakage through this metal-to-metal joint.
6. The vertical portion of the transverse seam sealant joint failed to resist water penetration when water was ponded on the mockup to a level greater than 19 mm ( $\frac{3}{4}$  in.). Shearing action of the bridge seal applied at this location caused voids to develop and the sealant to fail along the bottom edge of the standing seam at the folded side during the mechanical movement. Failure of the sealant may also be attributed to the incompatibility of the silicone and butyl sealant within the seam. Debonding of the silicone sealant at the upturn panel edge created a void for

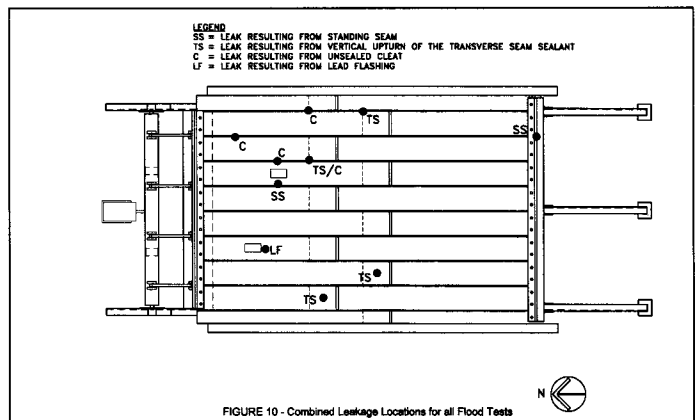


Figure 10.



water to infiltrate at transverse seam locations.

7. The flashing surrounding the davits was a two-piece lead boot that was soldered to the TCS panels, clamped to the top of the steel davit with a drawband, and sealed with butyl sealant. Mechanical cycling caused small cracks to develop in the lead sheet and solder from metal fatigue, allowing water infiltration. Additionally, the butyl sealant and drawband at the top of the lead flashing separated from one of the davits after 3,000 mechanical cycles.
8. With the exception of leakage at the both davit locations, leakage in the original mockup did not occur at any time during the ASTM E 331 water spray testing and wind uplift tests. The height of the water allowed to pond on the panels had a direct correlation to leakage. Water ponded to a height of approximately 19 mm ( $\frac{3}{4}$  in.) did not result in leakage, excluding the davit locations. Leakage did occur, however, when water was ponded above 19 mm ( $\frac{3}{4}$  in.). The center of the folded edge of the standing seam is the critical height for leakage to occur, excluding wind driven rain.
9. Calculations taking into account drainage flow on a curved roof indicated that the height of the water resulting from a 100-year rainfall intensity for a duration of 10 minutes would reach a maximum of 17.5 mm (0.69 in.). The level of water during these rains will be from 7.4 mm to 17.5 mm (0.3 to 0.69 in.) plus the thickness of the sealant at the transverse seam, or approximately 22 mm to 29 mm ( $\frac{7}{8}$  to 1  $\frac{1}{8}$  in.). Raising the standing seam above 25 mm (1 in.) will significantly improve the watertightness of the metal at the transverse joints because the bottom of the folded portion of the seam will be elevated above anticipated design rainfall levels.

## RECOMMENDATIONS TO IMPROVE WATERTIGHTNESS

As a result of the testing program performed on the mockup of the roofing system, the following recommendations would improve the watertightness and performance aspects of the design:

1. Installation of the SAM is critical to provide a second line of defense against leakage. Special care must be taken when forming the membrane at laps and corners around davits. These details should include the use of a liquid membrane to seal and enhance the watertight performance of the laps in the membrane.
2. Openings cut in the standing-seam panels for the davits should be made through the flat portion of the pan only and not through the standing seams.
3. Davit boot flashing should include a flexible connection to the steel davits using an elastomeric sheet membrane.
4. The height of the standing seam should be raised so that the maximum water flow above the sealant at transverse seams will be below the bottom edge of the double lock seams.
5. Stainless steel expansion cleats should be installed on the entire roof system in lieu of friction cleats to reduce the shearing action of the seam sealant. Set the expansion cleat in sealant onto the panel to avoid a metal-to-metal joint.
6. Install pre-formed silicone sealant "bridge seal" type seals at all transverse seams in the low-slope regions up to 3:12 (25 percent) slope.

## REFERENCES

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