PROCEEDINGS

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Roof Drainage Design, Roof Collapses, and the Codes

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Abstract

Every year, roofs in the United States collapse because of roof drainage-related design issues. These collapses result in large financial losses and serious safety consequences, including loss of life. This paper is the result of more than three decades of forensic investigations of dozens of catastrophic roof collapses, and addresses recent changes in the codes that have profound life-safety implications. The paper includes an in-depth discussion of drainage design fundamentals, flaws in current and past code design standards, examples of actual collapses, and the drainage design issues contributing to the collapses.

Speakers

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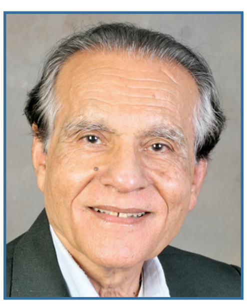

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Roof Drainage Design, Roof Collapses, and the Codes

1. INTRODUCTION

Every year, there are several catastrophic collapses of roofs in the United States related to roof drainage, resulting in prolonged legal proceedings that involve the consideration of life-safety consequences and monetary losses from property damage, business interruptions, inventory loss, losses to employees, and legal costs.[1,2,3] Almost all drainage-related roof collapses occur in relatively flat (low-slope) roofs with parapet walls that have inadequate provisions for overflow. Roofs that drain water over the edges of the roof into external gutters and downspouts are not as subject to such collapses and, hence, are not reviewed in this paper. This paper addresses collapses occurring in parapeted low-slope roofs with internal roof drains and/or scuppers.

Figure 1 – A typical drainage-related collapse of a low-slope roof. Photo by Stephen Patterson.

Most such collapses occur in one-story, large-footprint, big box-type (warehouse and retail-type) buildings, whose roofs consist of long-span, lightweight steel framing members, typically using open-web joists and joist girders. Designed to the minimum permissible code design criteria, they are prone to collapses when the load from rainwater accumulation on them exceeds the design values. An example of such a collapse is shown in *Figure 1*. Note that small-footprint buildings or reinforced concrete frame buildings are less likely to collapse from the accumulation of water.

There are several reasons for the collapses just mentioned. The important ones, discussed in greater detail in subsequent sections, are as follows:

1. A large number of existing buildings were built before the codes addressed requirements related to roof slope and overflow drains or scuppers. Many, if not most, of these buildings have inadequate overflow and/or slope.
2. The steel structure is one of the most expensive parts of a large box-type building. Reducing steel tonnage by increasing the spacing and spans of framing members has a pronounced effect on the overall cost of the building. The reduction in steel lowers the strength and stiffness of components and increases the likelihood of a collapse.
3. Low-slope roof drainage design, though theoretically simple, is complicated by the fact that it involves the input of three design professionals: the project architect, the structural engineer, and the plumbing engineer (*Figure 2*). Educated in disparate disciplines, few of these professionals have a comprehensive understanding of drainage design and its relationship with the building's structure. Therefore, although the respective roles of each in the design process are articulated in practice regimes, putting the entire design together is not. Each design discipline assumes that if they design their specific part to meet the code, their job is done and the building is safe.

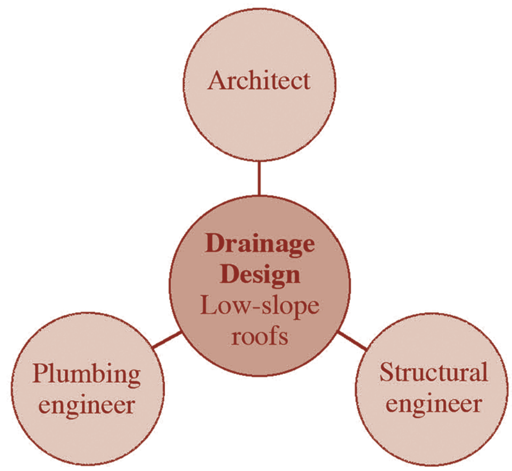


Figure 2 – Professionals involved in the design of drainage systems of low-slope roofs. (This illustration applies only to new construction. In reroofing, the design professionals may not be involved.)

In practice, therefore, there is a general lack of communication and/or coordination among the three members. This can yield a faulty design, which can be aggravated by poor execution by the contracting community and deterioration of the building due to age, resulting in a collapse under unfavorable weather conditions.

4. It is generally forgotten that code provisions are minimum requirements, often arrived at through consensus of only those stakeholders who are present in code development meetings. The provisions may not be comprehensive, may ignore important design considerations, and often do not represent the best of building science information.

Lack of due diligence by the design professionals to obtain appropriate guidance from standards and other publications can subsequently present a serious problem.

For example, neither the International Building Code (IBC) nor the International Plumbing Code (IPC) addresses the drainage flow rates through roof drains as a function of hydraulic head. The information given in the IPC is the maximum drainage capacity of roof drains of various sizes with no reference to the hydraulic head (*Figure 3*), erroneously implying that the hydraulic head is not a consideration in the drainage design process.

The problem is more serious with scuppers, as there is no information related to scupper design in the IBC or the IPC, which leaves it to the designer to seek it. To the best of the authors' knowledge, the 2003 RCI Foundation (RCIF) monograph, titled *Roof Drainage*[4] is one of the few publications that deals comprehensively with scuppers.

5. The requirement for overflow drains or scuppers did not appear in building codes until the 1960s, and slope was not addressed in them until the 1980s. Consequently, many existing buildings have inadequate or no overflow drains at all and are at risk of their roofs collapsing.
6. Since the 1980s, there has been a gradual weakening in several requirements of the regulatory apparatus (building code and plumbing code provisions) related to roof slope and overflow drainage. For example, when roof system replacement (referred to as "reroofing") takes place, it must conform to the provisions of various codes in force at the time of reroofing. Because roof drainage is intimately related to the roof system (functioning as the carrier for rainwater), a reroofing should automatically trigger a scrutiny of the existing drainage system of the building, so as to bring it to par with the provisions of the current building and plumbing codes.

   This, however, is not the case today. The 2015 IBC has, for the first time since its introduction, eliminated the requirements for the building's drainage system to meet the code's drainage requirements when reroofing, setting a dangerous precedent, discussed in detail in Section 2(v).

"**Roof Drainage**

Section 3207. (a) General. Roof systems shall be sloped a minimum of 1/4 inch in 12 inches for drainage. See Section 3205(f).

(b) Roof Drains. Unless roofs are sloped to drain over roof edges, roof drains shall be installed at each low point of the roof.

Roof drains shall be sized and discharged in accordance with the Plumbing Code.

(c) Overflow Drains and Scuppers. Where roof drains are required, overflow drains having the same size as the roof drains shall be installed with inlet flow line located 2 inches above the low point of the roof, or overflow scuppers having three times the size of the roof drains may be installed in adjacent parapet walls with inlet flow line located 2 inches above the low point of the adjacent roof and having a minimum opening height of 4 inches.

Overflow drains shall be connected to drain lines independent from the roof drains."

Figure 4 – Excerpt from Chapter 32: "Roof Construction and Coverings," 1988 Uniform Building Code.

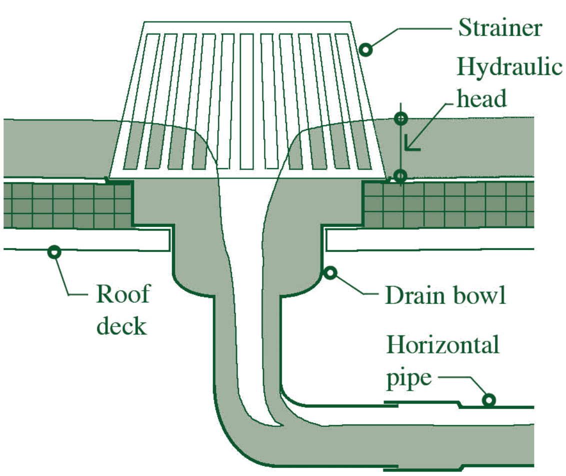


Figure 3 – Hydraulic head over a roof drain is an important determinant of flow rate through it.

WHAT THIS PAPER ADDRESSES

This paper is the result of the forensic work of its primary author on several dozen roof collapses over a span of 40 years, with research collaboration provided by the secondary author. Its basic purpose is to highlight the deceptive simplicity of low-slope roof drainage design, which can be quite complex in practice because of its multidisciplinary nature. The situation has been aggravated by the regulatory provisions not keeping apace with the demands of the profession. In fact, the reverse has happened as some regulatory provisions have become increasingly more permissive.

Therefore, the paper begins with a discussion of drainage design provisions for low-slope roofs. Because roof collapses more frequently occur in buildings designed in the past, a brief discussion of how the drainage design provisions have evolved is provided in the same section. A comprehensive discussion of drainage design fundamentals and the various parameters that must be considered during the design development stage are provided next, followed by a few design examples selected from recent roof collapses.

2. DRAINAGE DESIGN PROVISIONS FOR LOW-SLOPE ROOFS

The basic elements of proper low-slope roof drainage design are:

- Overflow drainage
- Roof slope
- Hydraulic head over the overflow drains or scuppers
- Rain loads due to ponded water
- Design rainfall rates for primary drainage and overflow drainage
- Verification that the roof structure has been designed to carry the rain load
- Investigation of the roof structure for ponding instability

Overflow Drainage and Roof Slope

The earliest direct mention of overflow drainage appeared in the 1964 Uniform Building Code (UBC) when it required the overflow drains or scuppers to be installed 2 in. above the low point of the roof. There was no requirement for roof slope and no

"**General**
Sec.3209. All reroofing shall conform to the applicable provisions of Chapter 32 of this code…
Inspections
Sec. 3210. New Roof coverings shall not be applied without first obtaining an inspection by the building official and written approval from the building official. A final inspection and approval shall be obtained from the building official when the reroofing is complete. The pre-roofing inspection shall pay particular attention to evidence of accumulation of water. Where extensive ponding of water is apparent, an analysis of the roof structure for compliance with Section 3207 shall be made and corrective measures, such as relocation of roof drains or scuppers, resloping of the roof or structural changes, shall be made."

Figure 5 – Excerpt from Appendix Chapter 32: "Reroofing," 1988 Uniform Building Code.

reference to plumbing codes or standards.

The requirement for providing roof slope first appeared in the 1988 UBC (Section 3207), requiring a minimum ¼-in.-per-ft. slope. The provision for overflow drains or scuppers was also a part of the code, along with reference to the plumbing code for sizing the roof drains. The minimum required opening height of scuppers was 4 in. (*Figure 4*).[5]

The provision of overflow drainage and a minimum ¼-in.-per-ft. slope are now universally accepted design requirements. They are a part of the 2015 IBC for roofing (except for reroofing, covered at the end of this section). A ¼-in.-per-ft. slope helps ensure rapid drainage and reduces the probability of ponding instability.

In many ways, the 1988 UBC was a high point for roofing and reroofing provisions with respect to roof drainage, as it required that all reroofing shall conform to the same provisions of the code that are applicable to (new) roofing, including the minimum slope and overflow requirements. In other words, no distinction was made between the provisions for roofing and reroofing (*Figure 5*).[6]

The 1988 UBC also required roof inspection before starting to reroof in addition to a professional analysis of the roof structure if extensive ponding of water was observed. Inspection of the roof after reroofing was also required. Sadly, these requirements were deleted from the subsequent versions of the UBC and never included in various editions of the UBC or the International Building Code (IBC) that followed.

The 1988 UBC did not provide any rational procedure for determining the scupper size except to state that the scupper opening area must be at least three times the roof drain area (*Figure 4*). It was a flawed provision because the scupper's opening size is a function of the head of water at the scupper—necessary to provide the required flow rate. Significant and unsafe buildup of water can easily occur on a roof using 1988 UBC criterion (see Example 2 under the section on Determining the Depth of Ponded Water on a Roof).

Hydraulic Head and Rain Load

The requirement for determining the rain load—load of water accumulating on the roof (with all primary drains blocked)—was first introduced in the 1988 publication of the ANSI/ASCE7-88 standard. The consideration of rain load on low-slope roofs from ponded water is now a standard requirement for the design of all low-slope roofs with raised edges. However, none of the code publications (in their various editions) provide any design aid or guidance for determining the depth of ponded water.

The first such design aid appeared in the 1994 Standard Plumbing Code (SPC)[7] and subsequently in 1995 edition of ASCE/SEI 7-95 standard[8] and remained unchanged up to ASCE/SEI 7-10 standard,[9] but was updated in ASCE/SEI 7-16 standard (see Section 4, Table 2).

Primary Drainage, Overflow Drainage, and Design Rainfall Rate

That the primary and overflow drainage systems should be completely independent of each other has been mandated by the codes since 1964. Each system was to be designed using the maximum of one-hour rainfall with a mean return period (MRP) of 100 years. However, the 1991 SPC made a significant change by requiring that the overflow drainage system be designed for 15-minute rainfalls with a 100-year MRP. The 15-minute, 100-year MRP rainfall is approximately twice the one-hour, 100-year MRP rainfall, providing the necessary safety provision against roof collapses (see Section 7).

The first International Plumbing Code (IPC), published in 1995,[10] required that the drainage capacities of roof drains given in IPC tables be divided by a factor of two for the design of overflow systems. This provision effectively doubled the design rainfall rate for overflow drainage, making it virtually identical to the 1991 SPC provision.

Unfortunately, the IPC, which became the governing plumbing code after the merger of all three legacy codes into the International Code Council (ICC) in 2000, eliminated the effective doubling of design rainfall rate for overflow drainage design. The current (2015) IPC requires the overflow drainage system to be designed for the same rainfall as the primary drainage system (one-hour rainfall with a 100-year MRP).

Based on the analysis of several roof collapses and the study of hydrological cycles, the authors had recommended the use of 15-minute, 100-year MRP rainfall for overflow drainage design in the monograph on Roof Drainage, published by the RCI Foundation (RCIF) in 2003.[11]

"**8.4 Ponding Instability**
"Ponding" refers to the retention of water due solely to the deflection of relatively flat roofs. Susceptible bays shall be investigated by structural analysis to assure that they possess adequate stiffness to preclude progressive deflection (i.e., instability) as rain falls on them or meltwater is created from snow on them. Bays with roof slope less than 1/4 in. per foot, or on which water is impounded upon them (in whole or in part) when the primary drain system is blocked, but the secondary drain system is functional, shall be designated as susceptible bays. Roof surfaces with a slope of at least 1/4 in. per foot (1.19°) toward points of free drainage need not be considered a susceptible bay. The larger of the snow load or the rain load equal to the design condition for a blocked primary drain system shall be used in this analysis."

Figure 6 – Excerpt from ASCE/SEI 7-10,* Minimum Design Loads for Buildings and Other Structures, *Chapter 8, Rain Loads.

Ponding Instability

Ponding instability is defined as the progressive increase in the accumulation (ponding) of water on the roof due to the lack of sufficient stiffness in roof framing. As the ponded water exerts load on the roof, the roof deflects, leading to greater accumulation of water, which further increases the roof's deflection. As the deflection increases, more water accumulates on the roof, increasing the deflection further, and so on—leading to the roof's ultimate collapse. Note that ponding instability may also occur from the accumulation of snow or the combined effects of snow and rain.

The consideration of ponding instability has been a part of the codes and standards for a long time. As previously indicated, IBC and ASCE/SEI 7 standards do not require the investigation of ponding instability for roofs with a slope greater than or equal to ¼ in. per ft. (*Figure 6*).[12] As shown in Section 6, this carte blanche assumption is incorrect. Therefore, roofs designed for slope equaling or exceeding ¼ in. per ft. may need to be checked for ponding instability.

Code Provisions for Reroofing

As shown in *Figure 5*, at one time, the drainage-related code provisions for reroofing were the same as for roofing (including those for overflow drainage and roof slope). However, gradually, the reroofing provisions have been watered down. Several years ago, the requirement for a minimum roof slope (¼ in. per ft.) was eliminated and replaced by the requirement that the existing roof should provide positive drainage.

Positive drainage is defined in 2015 IBC (Section 202) as "the drainage condition in which consideration has been made for all loading deflections of the roof deck, and additional slope has been provided to ensure drainage of roof within 48 hours of precipitation." Water standing on a roof for two days is the definition of "poor drainage," not "positive drainage."

Eliminating the requirement for ¼-in.-per-ft. slope has been a retrograde step because:

1. The criterion is imprecise and has no relationship to good drainage.
2. Water should drain freely and quickly and not stand on a roof for an extended period of time, let alone two days.
3. Hardly any roofing contractor will test the roof (before reroofing) by flooding it, then waiting for 48 hours to observe the areas where the water is still present.
4. There is no mandate in the code for a third-party inspection of the process and how the faulty situation is to be corrected.
5. A roof could be dead flat, surrounded by parapet walls without any overflow drainage, and could still meet the requirement of positive drainage, while remaining highly prone to ponding instability and collapse.

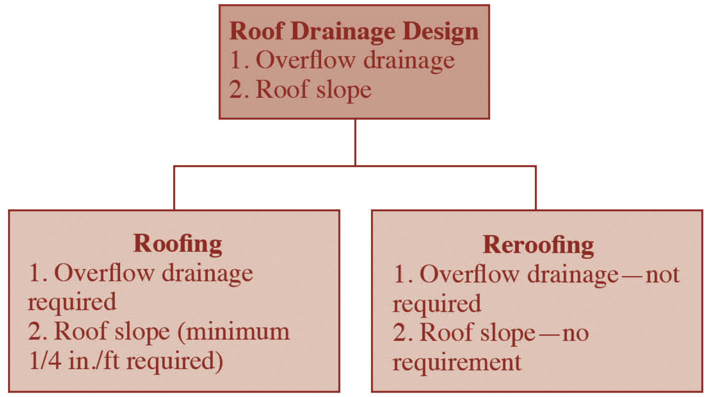


Figure 7 – Comparison of the requirements for overflow drainage and roof slope for roofing and reroofing in 2015 International Building Code [Ref. 13].

A more serious degrading of reroofing provision occurred with the 2015 IBC, which deleted the requirement for the overflow drainage if the existing roof was not previously provided with one. Additionally, if the overflow drainage exists and is below the current code, an upgrade is not required. Reroofing provisions, as they exist in the 2015 IBC, are illustrated in *Figure 7*.[13]

3. THE BASIC PROBLEM

The problem is that many, if not most, existing buildings were built either with no overflow drainage or an inadequate overflow. It is a serious design and construction defect that has the potential for catastrophic consequences. The most logical time to correct the situation in such cases is when the roof is replaced.

The argument made against making the correction is that if the building has performed well during all its previous years and even decades, it will perform well in the future as well. The argument is made not only by laypersons but also by some architects, engineers, and even by the code officials, who are supposedly the guardians of ensuring health, safety, and welfare in buildings.

One of the first collapses the primary author investigated was a 30-year-old grocery store with scuppers as the primary drainage and no overflow drainage. In 30 years, there was no problem until someone threw a Fort Worth Star-Telegram Sunday newspaper on the roof. The newspaper floated into the scupper, forming a perfect plug, resulting in a catastrophic collapse. Fortunately, no one was hurt.

There is a chance that had it not been for the newspaper, the buildings would have never collapsed, but it happened. As consultants and designers, we cannot (and are not permitted to) rely on chance. In another grocery store collapse investigated by the primary author, blocked scuppers caused a collapse that claimed two lives. (Unfortunately, the conditions that led to these failures are now permitted in the Reroofing section of the 2015 IBC.)

The primary author recently inspected the collapse of a large warehouse facility in the Dallas area that was constructed in the early 1980s. The roof had 1/8-in.-per-ft. slope, which met the code requirements at the time it was constructed. There was no significant ponding of water. The roof drained freely and exceeded the requirements for "positive drainage." The roof drains were slightly oversized per the design requirements of the UBC in force at the time of its construction; i.e., it was overdesigned per the requirements of 2015 IBC.

The overflow drainage was provided through scuppers, which were sized based on the then-applicable UBC provision, requiring that scupper opening area should be at least three times the area of the roof drains (see Section 2, Overflow Drainage and Roof Slope.) The evidence suggested that the roof drains were blocked with debris.

Our calculation indicated that, assuming the drains were blocked, the rain load on joists would be in excess of two times the typical design live load for the joists. These calculations did not take into account the additional load that could possibly occur from positive wind load on the roof. In other words, a roof drainage design can meet the code in force at the time when the building was built, but the roof can still collapse.

4. DETERMINING THE DEPTH OF PONDED WATER ON A ROOF

The determination of rain load on a roof requires calculating the depth of ponded water. This must be preceded by the design of both the primary and overflow drainage systems. The drainage system design is based on one-hour, 100-year MRP rainfall for the location and the use of IPC table for the drainage capacities of drains of various sizes, shown in *Table 1*.[14]

The process just described will be illustrated using two examples. In Example 1, both primary and overflow drainage systems consist of roof drains. In Example 2, the primary system consists of roof drains and the secondary system consists of scuppers.

Example 1

In consultation with the architect, the project's plumbing engineer has prepared the layout of roof drains for a 300-ft. x 450-ft. distribution center (*Figure 8*). The roof slopes ¼ in. per ft. on either side of a central ridge, and the drains are located 90 ft. on center along the 450-ft.-long parapets (five drains next to each parapet)—a total of ten drains on the roof. It has been decided to use a side-by-side combination of primary and overflow drains, with inlet of the overflow drain elevated 2 in. above that of the primary drain, using an overflow collar dam.

The architect has asked the plumbing engineer to provide 1) primary and overflow drain sizes conforming with 2015 IPC and 2) the depth of ponded water on the roof when the primary drains are blocked. The one-hour, 100-year MRP rainfall for the location is 4 in.

Plumbing Engineer's Solution

Total roof area =
300 x 450 ft. = 135,000 sq. ft.

Total rainfall on roof in 60 minutes =
135,000 sq. ft. (4 in.) = 45,000 cft

Total rainfall on roof in 1 minute =
(45,000/60) = 750 cft =
750 x 7.48 = 5610 gallons

(Note: 1 cft = 7.48 gallons.)

Because the roof contains ten drains, the minimum required flow rate of each drain = (5610/10) = 561 gpm.

From *Table 2*,[15] the primary drainage system will comprise 6-in.-diameter drains. The flow rate of each drain = 563 gpm > 561 gpm (minimum required flow rate).

The 2015 IPC requires that the overflow drains have the same flow rate as the primary drains. Therefore, the overflow roof drains will also be 6 inches in diameter.

While the 2015 IPC provides the flow rates of roof drains, it does not provide the head of water that must exist over the drain to produce that flow rate. To determine the head of water corresponding to the flow rate, we refer to ASCE/SEI 7-16 Standard data, given in *Table 1*. From this table, the head of water for the flow rate of 561 gpm is approximately 5.5 in.

Thus, the total depth of water on the roof when the primary system is blocked = static head + hydraulic head = 2.0 + 5.5 = 7.5 in. (*Figure 9*). This information is sent to the project architect for onward transmission to the structural engineer for determining the rain load and the design of the roof assembly. The weight of water corresponding to a depth of 7.5 in. = (5.2)(7.5) = 39.0 psf.

(Note that this example does not provide the entire drainage solution, as the remaining part is not relevant to this paper; i.e., the design of below-deck drainage elements, such as tail pipes, horizontal pipes, and the conductors.)

Drain diameter (in.)	Drainage capacity (gpm)
3	92
4	192
6	563
8	1,208

Adapted from 2015 International Plumbing Code [Ref.14].

Table 1 – Maximum flow rate (drainage capacities) of roof drains in gallons per minute.

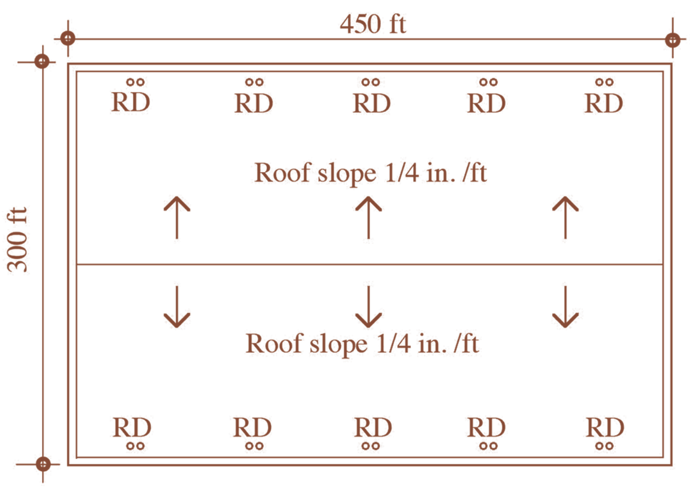


Figure 8 – Roof plan of the building in Example 1. RD is the acronym for "roof drains"—in this case, a set of primary and overflow drains.

Hydraulic head (in.)	Flow rate (gpm)	Hydraulic head (in.)	Flow rate (gpm)
0.5	50	3.5	400
1.0	100	4.0	450
1.5	150	5.0	500
2.0	200	5.5	550
2.5	250	6.0	600
3.0	300		

Adapted from ASCE/SEI 7-16 Standard: *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* [Ref. 15].

Table 2 – Flow rate through a 6-in.-diameter roof drain as a function of hydraulic head.

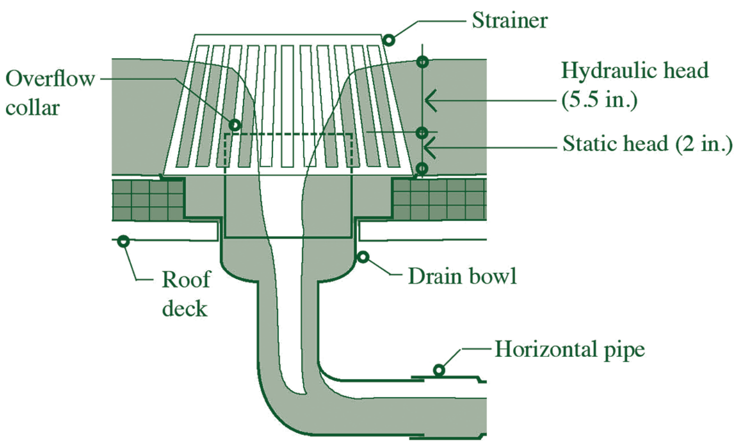


Figure 9 – Hydraulic head and static head over the overflow drains of the building of Example 1 (not to scale).

Example 2

The project architect of the building of Example 1 has asked the plumbing engineer to provide an alternative drainage solution in which the overflow drainage will be provided by scuppers located close to each primary drain.

Plumbing Engineer's Solution

Minimum required flow rate of each scupper = 561 gpm

The flow rate of a scupper is given by the following equation:

$$Q = 2.9\,(L)\,H^{1.5}$$

Equation 1

Where Q = flow rate through scupper (gpm), L = length of scupper opening (in.), and H = head of water (in.)

Setting Q = 561 and L = 18 inches in Eq. (1), we obtain H = 4.87 in., (say 5.0 in.). Because the inlet level of the scupper is raised 2 in. above the primary drain, the head of water at its lowest point = 2.0 + 5.0 = 7.0 in. This information is sent to the architect. The weight of water (at the lowest point on roof) corresponding to a depth of 7.0 in. = (7.0)(5.2) = 36.4 psf.

The scupper opening size = 18 in. x 6 in. (Note: A minimum 1-in. clearance is required above the head of water.) The total scupper opening area = 108 sq. in. Note that the scupper opening height of 6 in. is greater than the 4-in. minimum required by 2015 IPC.

Authors' Observations

It is the authors' experience that the design process illustrated in the given examples seldom occurs in practice. In theory, the plumbing engineer should calculate the head of water above the overflow drains or overflow scuppers and submit this information to the architect who, after reviewing it, would send it to the structural engineer. However, the code places the responsibility on the structural engineer (who is typically unfamiliar with plumbing design and the issues discussed in this paper) to verify that the structure will support the load from rainwater accumulation.

In both examples, the rain load at the lowest point on the roof (39.0 psf in Example 1 and 36.4 psf in Example 2) are greater than the roof's design live load of 20 psf. They are much greater if the live load reduction has been assumed by the project's structural engineer.

It is worth pointing out that it is difficult to locate scuppers 2 in. above the low point of a roof because of crickets and other variations in rooftop elevation (*Figure 10*). Consequently, the scuppers are typically located 4 in. above the roof's low point, which further increases the depth of water. In the case of Example 2, this will give a ponding depth of 9.0 inches in place of 7.0 inches, increasing the weight of water at the lowest point of the roof to 46.8 psf in place of 36.4 psf.

Returning to the 1988 UBC's (arbitrary) provision that the overflow scupper opening area be three times the primary roof drain area, we see that in Example 2, the scupper opening area = 108 sq. in. The area of each 6-in.-diameter roof drain = 28.27 sq. in. Hence, three times the area of roof drains = 84.81 sq. in., which is well below that obtained from rational analysis (108 sq. in.) in Example 2.

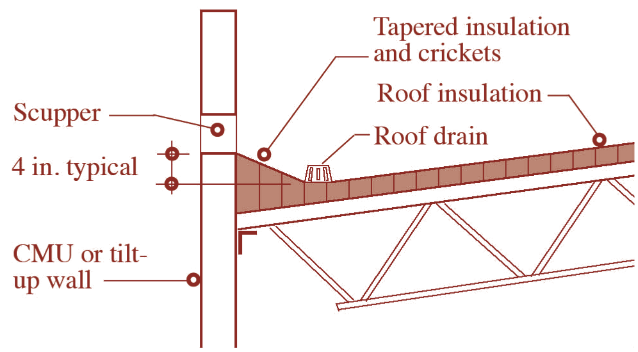


Figure 10 – Because of crickets and tapered insulation near a parapet wall, the typical difference between the inlet levels of scupper and the primary roof drain is 4 in. or greater.

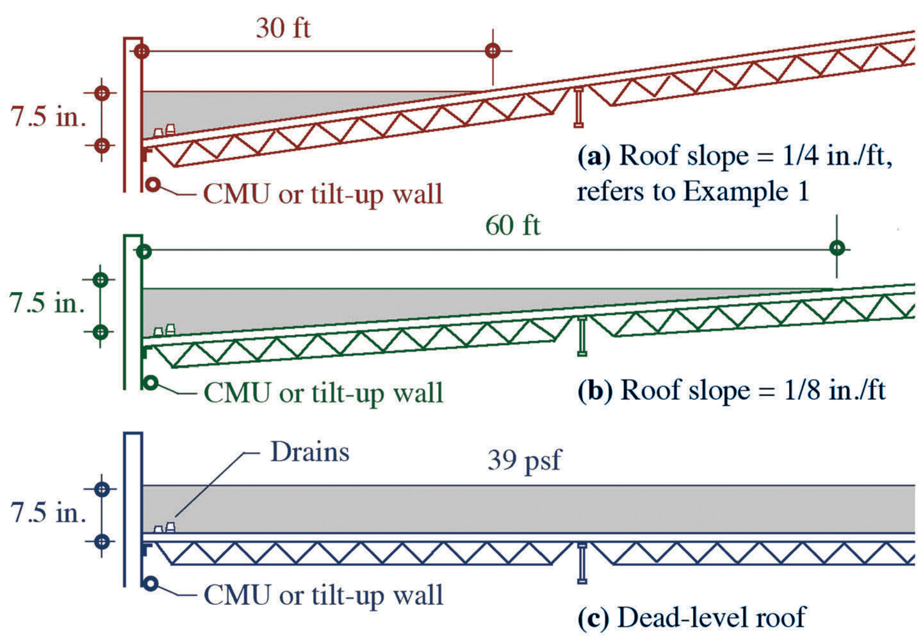


Figure 11 – Effect of roof slope on rain load on a roof. The maximum rain load in all three illustrations is 39.0 psf. The rain load distribution shown in illustration (a) relates to the building of Example 1.

5. IMPORTANCE OF ROOF SLOPE

To know the depth of water at the low point of the roof is the first step in determining the rain load on the roof. The next step is to account for the roof's slope, which affects the total rain load on the roof and its distribution. *Figure 11(a)* illustrates the distribution of load on the roof of Example 1. Assuming that the joist span is 45 ft., the rain load extends to a length of 30.0 ft. over the first joist.

Note that the total load on the first joist of *Figure 11(a)* is [0.5(39.0)30] = 585 pounds, which is equivalent to a uniform load of 19.5 psf over a 30-ft. length of joist. The high concentration of load near the parapet may cause deflection-related distress in the deck and local failure of the joist, but is not likely to cause ponding instability because the deflection of the joist should normally not exceed the allowable deflection.

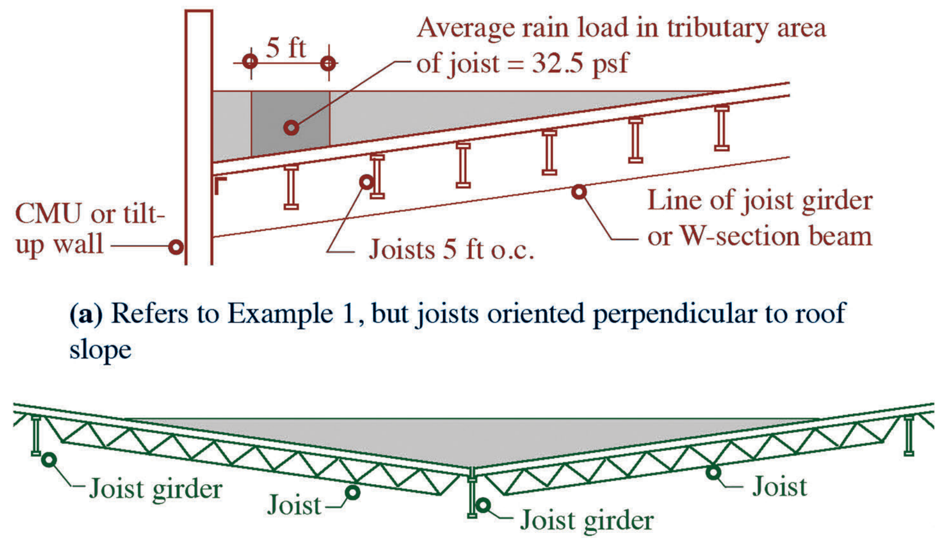
If roof slope is 1/8 in. per ft., the submerged area of roof is 60.0 ft. long (*Figure 11(b)*). In this case, the rain load on the roof extends over two joists and is twice that of *Figure 11(a)*. The average load on the first joist = 0.5[39 + 39(15/60)] = 24.4 psf, which exceeds the design load of 20 psf, indicating a fair probability of ponding instability in a framing system designed to the minimum structural design provisions of the code.

If the roof were dead flat, the entire roof would be submerged in water (*Figure 11(c)*). In this case, the entire roof is under a load of 39.0 psf. This is 95% greater than the live load of 20 psf and 144% greater than 16 psf (if live load reduction was assumed in the design of the joists). This roof is the most likely candidate for ponding instability failure, unless its structural framing has been designed with adequate stiffness to prevent it.

The illustrations in *Figure 11* highlight the importance of roof slope in the structural design of the building for ponding considerations. They also explain why the building code historically required the roof structure to be analyzed for ponding instability if the roof slope was less than ¼ in. per ft.

6. ORIENTATION OF STRUCTURAL FRAMING AND DIRECTION OF ROOF SLOPE

Figure 11(a) shows the rain load on the roof of Example 1, where the secondary framing members of the roof (members that provide direct support to the deck, i.e., the joists) are oriented in the direction of roof slope. *Figure 12(a)* shows the rain load distribution of the same building, but the secondary framing members (joists) are oriented perpendicular to roof slope.



(a) Refers to Example 1, but joists oriented perpendicular to roof slope

(b) Joists parallel to roof slope, meeting in a valley

Figure 12 – Effect of the orientation of roof framing members on rain load.

Note that although the rain load distribution and the total rain load on the roofs of *Figure 11(a)* and *Figure 12(a)* are identical, there is great difference in their structural implications. In *Figure 12(a)*, the average rain load on the first joist is 32.5 psf along the entire span of the joist—much higher than the roof's design load. This situation is similar to the joist of the dead-flat roof of *Figure 11(c)*, and hence prone to ponding instability. (Note: In *Figure 12(a)*, we have assumed that the joists are spaced 5 ft. on center—typical for roofs with steel deck and steel joists.)

Figure 12(a) shows that the building code provision stating that a roof with a slope ≥¼ in. per ft. is not required to be investigated for ponding instability is not always correct. This observation is further endorsed by *Figure 12(b)*, where the joists from opposite directions are supported by a joist girder forming a valley, creating a possibility of substantial overload on the joist girder.

This situation is particularly serious because the tributary area of a typical joist girder is so large that it qualifies for the roof live load reduction of up to 40% by the building codes—from 20 to 12 psf. This can result in the design of joist girders that are highly deficient in stiffness and strength to support the weight of ponded water that may exceed the load for which they have been designed by 100% to 200%.

7. DESIGN RAINFALL RATE

The discussion and the examples provided thus far are based on the design rainfall rate as the maximum one-hour rainfall with an MRP of 100 years for both primary and overflow drainage. The design rainfall rate assumes that it is uniform within the entire one-hour duration. In other words, the assumption is that if the 100-year MRP rainfall at a location is 4 in. per hour, that location will receive 1 in. rainfall every 15 minutes, or 0.5 in. every 7.5 minutes, or (4/60) in. = 0.067 in. per minute.

The actual rainfall seldom occurs at a uniform rate, particularly during thunderstorms, tropical storms, and hurricanes. In such situations, bursts of rainfall may occur in short durations, but the one-hour rainfall may be the same as the design rainfall. Therefore, there is a strong rationale for using a higher design rainfall rate for overflow drainage.

Note that the primary drainage system is designed to drain water off the roof within a reasonable time. There are no life safety issues related to the primary drainage design. Therefore, designing the primary drainage system assuming a uniform rainfall rate is fine. The overflow drainage system, on the other hand, is the safety valve—to prevent unsafe accumulation of water on the roof. A strong rationale therefore exists that the overflow drainage design should account for the bursts of rainfall within short durations.

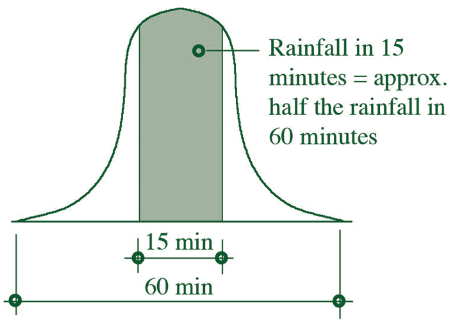


Figure 13 – Maximum 15-minute, 100-year MRP rainfall is approximately half of one-hour, 100-year MRP rainfall, implying that the rainfall rate in 15 minutes is twice the design rainfall rate.

Hydrological studies[16] have shown that a location can get half its one-hour rainfall in 15 minutes. Thus, if a location receives a 100-year MRP rainfall of 4 inches in one hour, it can receive up to 2 inches of rainfall in 15 minutes—a rainfall rate of 8 in. per hour. *Figure 13* illustrates this narrative.

In addition to the high rainfall rate over a short duration that can overload the roof, hailstorms are another problematic event for a drainage system. Small hail is particularly problematic as it can easily block or impede the flow. Because hail sometimes occurs with severe thunderstorms, one can expect a large amount of rainfall coupled with hail, increasing the probability of drain blockages.

The accumulation of debris on roofs is another problem related to roof drainage. Serious and frequent blockages of drains and scuppers from the accumulation of debris has been reported by investigators.[17] The types of debris found on roofs includes dirt, leaves, plastic bags, paper, soda cans, bottles, and so on. Although regular roof observation and maintenance can prevent this problem, it is neither enforceable nor practical.

Designing the overflow drainage with 15-minute-per-hour rainfall rate is an insurance, not only against nonuniform rainfall rate, but also against blockage caused by hail, as well as debris accumulation. As stated in Section 2 under "Ponding Instability," the 1991 SPC and 1995 IPC required the overflow drainage design to be based on 15-minute, 100-year MRP rainfall rates. There is a need to revert to that provision in future editions of the plumbing codes.

8. AUTHORS' INVESTIGATIONS AND ASCE/SEI 7-16 STANDARD

In Section 6, examples of how low-slope roofs of large-footprint, big-box-type structures can be substantially overloaded by ponded water and the resultant ponding instability, are given. Historically, the evaluation for ponding instability has been required on roofs with slopes ≤¼ in. per foot. For example, ASCE/SEI 7-05 Standard required: "Roofs with a slope of ¼ in./ft. (1.19°) shall be investigated for structural analysis to assure that they possess adequate stiffness to preclude progressive deflection (i.e., instability) as rain falls on them or meltwater is created from snow on them."

The above provision was simplified in ASCE/SEI 7-10 Standard (see *Figure 6*) by requiring that "Susceptible bays shall be investigated by structural analysis to assure that they possess adequate stiffness to preclude progressive deflection (i.e., instability) as rain falls on them or meltwater is created from snow on them. ...Roof surfaces with a slope of at least ¼ in. per ft. (1.19°) towards points of free drainage need not be considered as susceptible bays."

The 2015 IBC refers to ASCE/SEI 7-10, published in 2010. ASCE/SEI 7-10 has now been replaced by ASCE/SEI 7-16, published in July 2017, and will be referenced in the 2018 IBC.

It is important to mention that the provisions of ASCE/SEI 7-16 for ponding instability analysis are far more stringent than those given in the standard's previous editions and agree with the authors' investigations, summarized in Section 6. This is a positive vindication of the many years of the authors' work on various collapses. ASCE/SEI 7-16 requires ponding instability analysis for the following conditions:

1. Bays with a roof slope less than ¼ in. per foot (1.19°) when the secondary members are perpendicular to the free draining edge,
2. Bays with a roof slope less than 1 in. per foot (4.76°) when the secondary members are parallel to the free draining edge,
3. Bays with a roof slope less than 1 in. per foot (4.76°) and a span-to-spacing ratio for the secondary members greater than 16 when the secondary members are parallel to the free drainage edge, or
4. Bays on which water accumulates (in whole or in part) when the primary drain system is blocked but the overflow drain system is functional. The larger of the snow load or the rain load equal to the design condition for a blocked primary drain system shall be used in this analysis.

ASCE/SEI 7-16 has also recognized the importance of a higher design rainfall rate for overflow drainage, as it now requires the 15-minute, 100-year rainfall rate. Section 8.2 of the standard states: "The design flow rate of the secondary (overflow) drains (including roof drains and downstream piping) or scuppers and their resulting hydraulic head (d_h) shall be based on a rainfall intensity equal to or greater than the 15-min duration/100-year return period (frequency) storm. Primary drainage systems shall be designed for a rainfall intensity equal to or greater than the 60-min duration/100-year return period (frequency) storm."

As the current IBC and IPC requirement for overflow drainage design are still based on 60-minute, 100-year MRP rainfall, the authors hope that in the 2018 editions of IBC and IPC, it will be revised to that required by ASCE/SEI 7-16. This will substantially reduce the potential for roof collapses. Not doing so will be tantamount to ignoring the expertise of the two major organizations—the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI)—that develop ASCE/SEI 7 with the help of several hundred engineering experts.

9. CONCLUSION

Roof drainage design is one of the most important roof design elements, and the overflow drainage design is its most critical part. The function of the overflow drainage is to prevent the roof from collapsing—an important life safety issue in roofs.

ASCE/SEI 7-16 has recognized the deficiencies in drainage design with respect to ponding instability and has made major revisions from its previous edition, which, when implemented, will dramatically reduce the potential for roof collapses. This is a major step forward at a time when the IBC has been moving in the opposite direction. The standard has also recognized the importance of the 15-minute duration rainfall rate for overflow drainage design. The ICC should re-evaluate the drainage design requirements in the IBC and IPC and provide appropriate provisions that are in compliance with ASCE 7-16 to ensure public safety.

This is equally important for reroofing because there is no reason why the IBC's requirements for reroofing should not be the same as for roofing in new construction. The costs involved to add overflow drainage at the time of reroofing (if it does not already exist) or to modify it to comply with the current code provisions for roofing are relatively insignificant compared with the monetary losses (not counting the injuries and fatalities) that may occur as a result of the collapses. Many existing buildings needlessly fall in the impending-collapse category, which can be easily prevented at the time of reroofing through overflow drainage. *Figure 14* summarizes the cost data case studies from two of the several collapses investigated by the primary author in support of this statement.

Additionally, there is a real problem with the definition and use of the term "positive drainage" in the IBC with respect to reroofing. Positive drainage as defined in the IBC is a poor and unworkable definition. By deleting the relationship between drainage efficiency and minimum ¼ in. per ft. slope, the IBC has placed the roofs of many existing buildings at more serious risk.

Fundamentally, any roof that has drainage issues—including, but not limited to the lack of appropriate slope or the lack of adequate overflow—should be evaluated by a design professional when a building is reroofed, in the same way as required for roofing.

Roof Drainage Correction Cost Data From Two Recent Collapses

1. Distribution Center, Dallas, Texas

Structural loss: approximately $4.0 million
Collateral damage (inventory loss + business interruption): approximately $34.0 million
Total monetary loss from roof collapse: $38.0 million
Cost to add overflow scuppers: approximately $10,000.

$$\frac{\text{Overflow drainage addition cost}}{\text{Total monetry loss}} = \frac{10{,}000}{38{,}000{,}000} = 0.00026 = 0.026\%$$

2. Distribution Center, Fort Worth, Texas

Structural loss: $5.0 million
Collateral damage (inventory loss + business interruption): approximately $35.0 million
Total monetary loss from roof collapse: $40.0 million
Cost to bring drainage system up to current code: approximately $150,000.

$$\frac{\text{Modified drainage system cost}}{\text{Total monetry loss}} = \frac{150{,}000}{40{,}000{,}000} = 0.0038 = 0.38\%$$

Figure 14 – Cost of correcting/modifying roof drainage system as a function of monetary loss from roof collapses. Note the data does not include life safety consequences from collapses.

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REFERENCES

1. Stephen Patterson. Forensic consulting related to roof collapses and private communications with several leading forensic consultants engaged in the same activity over a period of 40 years (unpublished).
2. J. Vamberskey. "Roof Failures Due to Ponding—A Symptom of Underestimated Development." *HERON*, Vol. 51, No. 2/3. Delft University of Technology and Corsmit Consulting Engineers. 2006. pp. 83-96.
3. John Lawson. "Roof Drainage—Not My Problem…May Be," *Proceedings of Structural Engineers Association of California (SEAOC) Convention*. 2012. pp. 136-151.
4. Stephen Patterson and Madan Mehta. *Roof Drainage*. Roof Consultants Institute Foundation (RCIF) Publication No. 02-03. 2003. p. 34.
5. International Council of Building Officials. "Roof Construction and Roof Coverings." *Uniform Building Code*. Chapter 32. 1988. p. 617.
6. Vamberskey. Op. cit. Chapter 32, Reroofing. p. 855.
7. *Standard Plumbing Code*. Plumbing-Heating-Cooling Contractors (PHCC) Association. Section 1109.3. 1994. p. 141.
8. American Society of Civil Engineers/Structural Engineering Institute. ASCE/SEI 7-95 Standard, *Minimum Design Loads for Buildings and Other Structures*. 1995. p. 187.
9. American Society of Civil Engineers/Structural Engineering Institute. ASCE/SEI 7-10 Standard, *Minimum Design Loads for Buildings and Other Structures*. 2010. p. 452.
10. International Code Council. *International Plumbing Code*. Section 1108.3. 1995. p. 358.
11. Patterson and Mehta. p. 73.
12. ASCE 7-10. p. 43.
13. American Society of Civil Engineers/Structural Engineering Institute. ASCE/SEI 7-05 Standard, *Minimum Design Loads for Buildings and Other Structures*. 2005. p. 95.
14. International Code Council. *International Plumbing Code*. 2015. p. 94.
15. American Society of Civil Engineers/Structural Engineering Institute. ASCE/SEI 7-16 Standard, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. July 2017. p. 509.
16. Patterson and Mehta. p 73.
17. Jim Koontz. "The Effects of Debris on the Flow Rates of Roof Drains and Scuppers." *Proceedings of the RCI 25th International Convention*. RCI, Inc. 2010. pp. 149-156.