Obstructions and ESFR Sprinklers – Phase 1

Final Report

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FOREWORD

ESFR sprinklers are often installed in warehouses to avoid installation of in-rack sprinklers. However, since the discharge pattern of ESFR sprinklers is different from standard-spray sprinklers, obstructions near the sprinkler heads can greatly affect the distribution of water. NFPA 13, *Standard for the Installation of Sprinkler Systems*, generally allows the following obstructions in Sections 8.12.5.1, 8.12.5.2, and 8.12.5.3:

- Sprinklers installed per the allowable distances from near or at ceiling obstructions in Table 8.12.5.1.1
- Isolated obstructions less than 2 feet wide and 1 foot or greater horizontally from sprinkler
- Isolated and continuous obstructions less than 2 inches wide and 2 feet or greater below deflector or 1 foot or greater horizontally from sprinkler
- Continuous obstructions 1 foot or less in width and located 1 foot horizontally from sprinkler
- Continuous obstructions 2 feet of less in width and located 2 feet horizontally from sprinkler
- Bottom chords of bar joists or open trusses located 1 foot or greater horizontally from sprinkler (upright sprinklers can be installed over the bottom chords of bar joists or open trusses that are up to 4 inches wide)

Two methods are available in NFPA 13 to resolve obstructions that do not fall into the categories above: eliminating the obstruction or adding sprinklers underneath the obstruction. However, there have been some successful tests that have been conducted with obstructions that are not allowable by NFPA 13 without taking these measures. The information from these tests as well as information gathered from further testing could help inform revisions to the NFPA 13 requirements.

The Fire Protection Research Foundation initiated this project to ultimately develop a tool that can be used for providing reliable analysis of the impact of obstructions on ESFR sprinklers based on existing test data and develop technical basis to the NFPA 13 Technical Committees for new requirements and guidance. The goal of this first phase project was to gather available test data, analyze the knowledge gaps, and develop a research plan for future testing.

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The content, opinions and conclusions contained in this report are solely those of the authors.

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Keywords: automatic sprinklers, ESFR sprinklers, warehouse fire protection, obstructions

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Literature Review and Test Plan

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1. Introduction

Early Suppression Fast Response (ESFR) sprinklers were developed to meet the demands of high challenge storage fire scenarios and are a common choice to protect warehouses. The added benefit to the use of this technology is in most cases, the requirement for rack sprinklers can be circumvented. Many aspects of ESFR sprinklers are unique compared to standard spray sprinklers. Paramount to ESFR sprinkler performance is the ability of the sprinkler to provide large amounts of water, in a specific discharge pattern, to the fire source in the incipient phase of fire development. Obstruction of the sprinkler discharge pattern could greatly affect the ability of the ESFR sprinkler to achieve fire suppression.

ESFR sprinkler obstructions requirements have for the most part, remained unaltered since the early development of the sprinkler. The requirements outlined in the 2013 Edition of NFPA 13, “Standard for Installation of Sprinkler Systems” (NFPA 13), are intended to limit the obstruction from inhibiting the spray pattern of the ESFR sprinkler. These requirements are based on a limited number of tests with conservative assumptions in addition to safety factors.

Current ESFR obstruction requirements are to locate the sprinklers a minimum of 12 inches horizontally from the nearest edge of any bottom chord or bar joist. A bridging member of 2 inches or less in width is to be located a minimum of 24 inches below the elevation of the sprinkler deflector or positioned a minimum of 12 inches horizontally from the sprinkler deflector. The ESFR design standards also limit the height of storage from being within 36 inches of the sprinkler deflector.

The absence of small and full-scale tests to understand and validate the obstruction requirements complicates one’s ability to interpret these requirements. The possibility to improve the current ESFR sprinkler obstruction requirements provided the motivation for the Fire Protection Research Foundation to commission this research project, “Obstructions and ESFR Sprinklers – Phase 1.”

The initial phase of this study reviewed relevant literature and sources made available to the team from the advising panel or through publically accessible sources. The background of the ESFR sprinkler development was also reviewed to better understand the possible effects obstructions have on ESFR sprinkler performance.

A fire-testing program was also outlined to establish a direction forward to explore the ESFR sprinkler obstruction issue.

2. Literature Review

A literature review was completed to compile and analyze available resources that evaluate the performance of an ESFR sprinkler with obstructions or literature that covers the development of the ESFR sprinkler standards.

The ESFR sprinkler relies on three important factors: the sprinkler response (response time index), the Actual Delivered Density (ADD), and the Required Delivered Density (RDD). ADD is defined as the water flux delivered to the top surface of a burning rack-storage array after penetrating the fire plume. RDD is defined as the water flux required to be delivered at the top of the burning storage array to achieve suppression.

The ESFR sprinkler is based on the concept of early suppression, whereby the activation of the sprinkler occurs during the early stages of a fire while the RDD is minimal. During the early stages of the fire, the ADD will exceed the RDD and thus provide an adequate density to suppress the fire[1].

The performance of a fire sprinkler can be measured by fire plume penetration, which is the ability of the sprinkler to deliver water droplets through the fire plume to the burning surface of the storage array. The penetration ratio is determined by the ADD divided by the Locally Applied Density (LAD) under a no fire condition[2]. The penetration ratio of an ESFR sprinkler does not change significantly with fire size (penetration ratio approaching 1.0), which highlights the superior performance of ESFR sprinklers.

Obstructions located near the sprinkler may redirect water or change the characteristics of the water droplet to the point that suppression of the fire would not be achieved (i.e., ADD<RDD). Additionally, water droplets may ricochet off the obstruction causing adjacent sprinklers to be wetted and thus not activate properly; a phenomenon termed cold soldering. This can lead to the operation of an excessive number of sprinklers or prevent the operation of sprinklers that are required for suppression.

The ESFR sprinkler has a specific and deliberately designed spray pattern much different from that of a standard spray or control mode sprinkler. The water density of ESFR sprinklers decreases with radial distance from the sprinkler axis. The area within the 2-foot radial distance has a significantly higher density than the measurements at 4, 6, 8, and 10 feet. The pattern was developed to suppress a fire located directly below the sprinkler with a high sprinkler to storage clearance (10 feet or greater), which is generally considered the most challenging fire location for ESFR sprinklers[3]. This discharge characteristic underscores the importance of not significantly obstructing the sprinkler in this critical region.

[1] Yao, C. (1988). The Development of the ESFR Sprinkler System. Fire Safety Journal, 14, 66 - 73.
[2] Yao, C. (1997). Overview of Sprinkler Technology Research. Fire Safety Science - Proceeding of the Fifth International Symposium (pp. 93 - 110). Melbourne, Australia: International Association for Fire Science.
[3] Chan, T.-S. (1994). Measurements of Water Density and Drop Size Distributions of Selected ESFR Sprinklers. Journal of Fire Protection Engineering, 79 - 87.

As part of the literature review, actual field obstruction conditions were identified. Obstructions relating to the commonly used structural roof system, open web steel joists, were evaluated. Dimensional parameters for the joists were reviewed to establish size generalities and trends. This information was used both to evaluate the practicality of the obstruction testing reviewed and to establish boundary conditions for the fire-testing program.

The size of the joists depends on three main factors: the required spans, design loads, and available space. The most common joist depth is 30 inches. The depth of the joist is related to the span of the joist and can be assumed equal to one-half of the span in inches[4]. For spans exceeding 60 feet, it was determined the joist depth of 35 inches is most common. For scenarios that have small spans or limited room joists, depths of 22 inches are commonly used.

The bottom chord of the joist consists of two double angles with equal length sides and is either welded or bolted together. The double angles can also vary in size depending on the application. For the most common scenario, 2-inch by 2-inch double angles are used for 30-inch deep joists. For joist exceeding this depth, the double angles are increased to 2½ inches by 2½ inches.

Obstructions are also caused by structural elements such as bridging used to provide support against lateral and other loads. The bridging members consist of a single angle. Size can also vary depending on the required loading. The most commonly found bridging member was determined to be a 1½-inch by 1½-inch angle.

Ten full-scale tests were identified as relevant to the study of ESFR sprinkler obstruction: seven tests containing obstruction scenarios and three containing plugged sprinklers. Out of the seven obstruction tests, only two failed, both due to the operation of an excess number of sprinklers (greater than 12). Table 1 summarizes the testing scenarios.

A series of ADD testing was completed by Mammoser & McCormick to analyze the effect of a bar joist or a bridging member on the ESFR sprinkler spray pattern. The testing consisted of over one hundred ADD tests using K-14 ESFR pendent sprinklers with different size bar joist and bridging members in various horizontal and vertical offsets.

[4] Braggs, L. (2014, June 25). Sales Engineer, Vulcraft. (W. Fletcher, Interviewer)

Table 1. Relevant ESFR Sprinkler Full-Scale Testing

Testing Report	Fire Performance Evaluation of Viking K-14 Suppression-Mode Upright Sprinklers			Fire Performance Evaluation of a K-16.8 Suppression-Mode Upright Sprinkler		The Development of the ESFR Sprinkler System	The Effect of Ceiling Bar Joist Obstruction Upon Suppression Performance of ESFR Sprinklers		Evaluation of ESFR Sprinkler Performance Obstructed by Bar Joist and Bridging Members in 40-Foot High Building	
Date	1999	1999	1999	2001	2001	1988	1999	1999	2006	2007
Test Type	OBST	OBST	PLUGGED	OBST	PLUGGED	PLUGGED	OBST	OBST	OBST	OBST
Test Name	VUK11	VUK12	VUK03	#3	#1	#6	#1	#2	#1	#2
Ceiling Height	30'	30'	30'	30'	30'		40'	40'	40'	40'
Storage Height	19.5'	19.5'	24.5'	19.5'	24.5'	23.75'	30'	30'	30'	30'
Commodity	Cartoned Meat Trays	FMR Standard Plastic	FMR Standard Plastic	Cartoned Meat Trays	FMR Standard Plastic	FMR Standard Plastic	Group-A Expanded Cartoned	Group-A Expanded Cartoned	Group-A Plastic Commodity	Group-A Plastic Commodity
Array	2X6X4	2X6X4	2X6X4	2X6X4	2X7X4	5 tiers	2X6X6	2X6X6	2X6X6	2X6X6
Target Array			1X4X5		1X4X5				1X6X4	1X6X4
Aisle									4'	4'
Ignition Center Below	1	1	2 (1 plugged)	1	2 (1 plugged)	2 (1 plugged)			1	1
K-Factor	K-14	K-14	K-14	K-16.8	K-16.8	K-14	K-14	K-14	K-14	K-14
Sprinkler Orientation	Upright	Upright	Upright	Upright	Upright	C/PF	Pendent	Pendent	Pendent	Pendent
Sprinkler Temp. (°F)	165	165	165	165	165	165	165	165	155	155
Pressure	50	50	50	35	35	50	75	75	75	75
Sprinkler Deflector from Ceiling	7"	7"	7"	7"	7"		14"	14"	14"	14"
Sprinkler Spacing	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'	10'X10'
Obstruction	Joist	Joist		Joist			Bar Joist	Bridging Member	Bridging Member	Joist and Bridging Member
Joist Depth	17"	17"		17"						28.5"
Obstruction Width	4"	4"		4"			4"	1.5"	1.25"X1.25" Angle	Joist - 1.5"X1.5" & Bridging Member 1.25"X1.25" Angle
Obstruction Position	10" Below Sprinkler Deflector	10" Below Sprinkler Deflector		10" Below Sprinkler Deflector			8" Below Sprinkler Deflector	8" Below Sprinkler Deflector	12" Below Sprinkler Deflector	Bridging Member - 12" Below Sprinkler Deflector & Bar Joist - 15.5" Below Sprinkler Deflector and 9.25" Offset Horizontally
Number of Sprinklers Activated	9	1	7	1	9	11	29	27	1	1
Peak Ceiling Steel Temp.	120	90	208	90	408		344	227	86	97
Fire Jump	No	No	No	No	UNK	Yes	UNK	UNK	No	No
Pallets Consumed	14	1.5	5	1.5	7	Main array - 5				
						Target Array - 1				

The Underwriters Laboratory (U.L.) third generation ADD apparatus was used to conduct the testing. Calibration of the fire plume of the apparatus to measurements of four-tier rack storage fires indicated that fire plume velocities and temperatures were generally within 10 percent of those measured for the rack storage fires[5].

ADD testing is a mandated testing protocol used in the ESFR sprinkler approval process by both FM Global and U.L. Although not a sole predictor of sprinkler performance, it can be used to determine boundaries within which full-scale testing scenarios can be developed.

To compare the reduction in ADD caused by the obstructions, an obstruction reduction factor (ORF) was calculated. The ORF is defined as the difference between the average ADD with an obstruction and the average ADD unobstructed, divided by the ADD unobstructed. Utilizing the ORF factor, a set of circumstances was judged more challenging or not challenging to the ESFR sprinkler system[6].

The series also compared the ADD results with and without a fire to determine the effect of the fire plume on the ESFR sprinklers. The results confirmed high penetration ratio values, which corroborates the conclusion that fire plumes have negligible effects on the ADD results within the ranges tested. The data from the ADD obstruction testing without a fire was not included in the analysis or figures in this report.

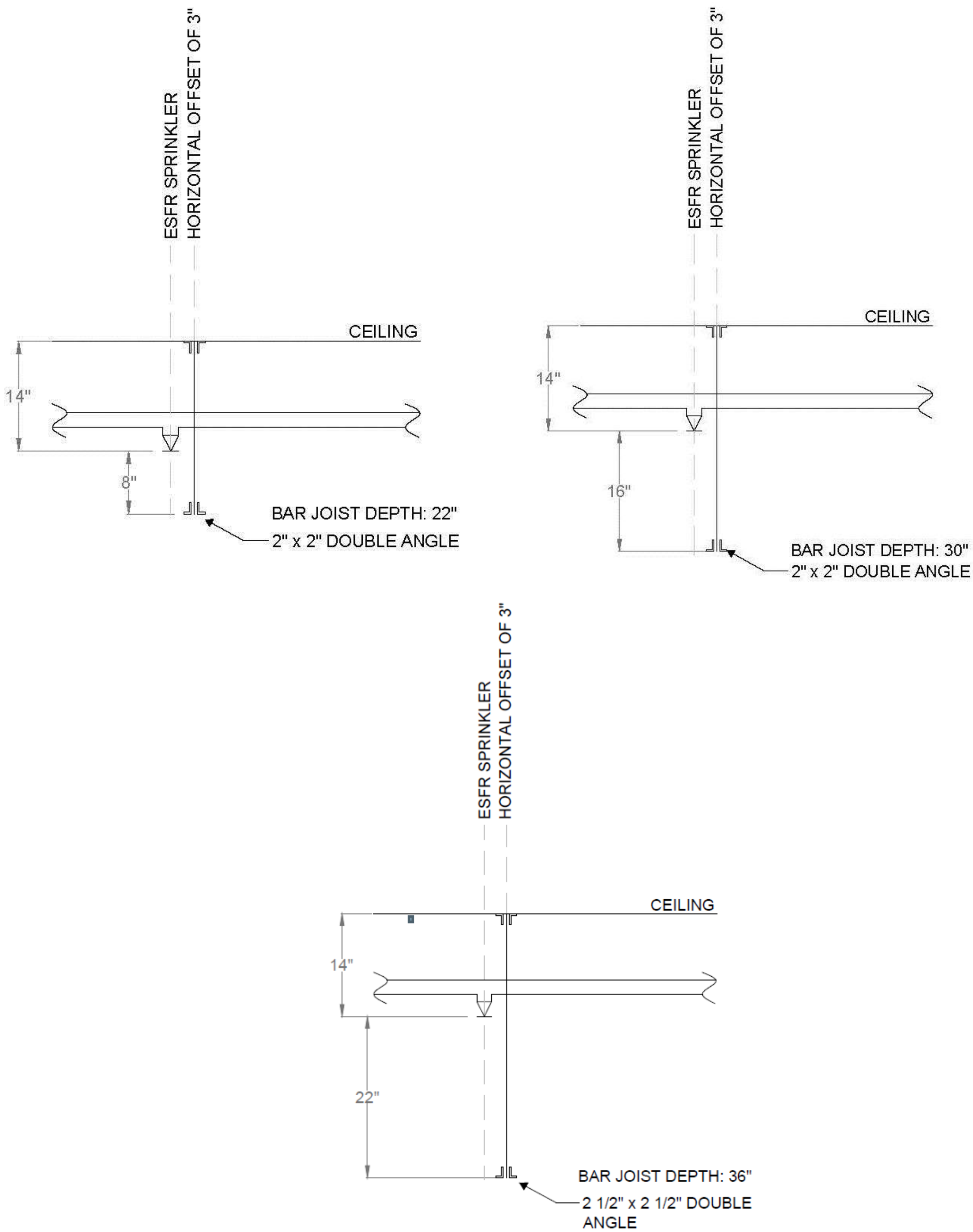
The fire used in the ADD obstruction testing was calibrated to represent a 1.5 MW fire using heptane flowing from nozzles located in the 6-inch flue spaces at the center of the array. The ADD apparatus was positioned so that the sprinkler was located underneath the intersection of the transverse and longitudinal flue spaces at the center of the array. The vertical distance from the top of the pans to the ceiling was a nominal 10 feet. A single test for each obstruction arrangement was performed. Each obstruction arrangement was tested using a sprinkler discharge of 50 and 75 psi, and with and without the fire.

The test series results showed that 22, 30, or 36-inch deep trusses located directly under the sprinkler would be challenging with discharge pressures of 50 or 75 psi. The 22-inch deep truss offset 3 inches would be challenging for a sprinkler with discharge pressures of 50 and 75 psi. A 30-inch deep joist offset 3 inches would not be challenging for a sprinkler with a discharge pressure of 75 psi. Lastly, a 36-inch deep joist offset 3 inches would not be challenging for a sprinkler with either discharge pressure. In general, the deeper the joist depth, the less the effect on the ADD, since the bottom chord of the joist was farther away from the sprinkler. See Figures 1A-C.

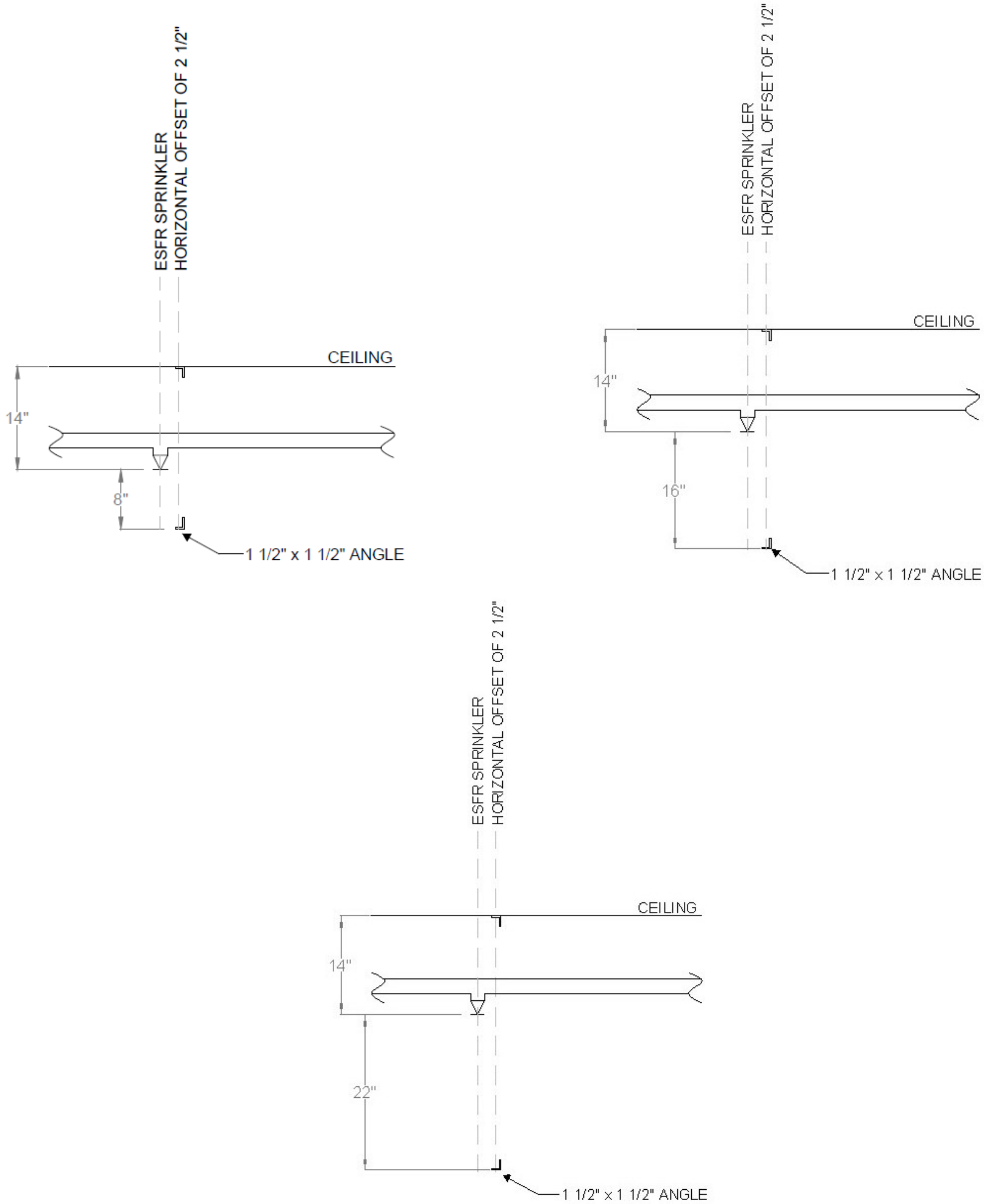
The bridging members were shown to be challenging with 1¼-inch or 1½-inch angles located 8 inches below the sprinkler deflector. The contour maps showed the obstruction sizes of 1-inch, 1¼-inch, and 1½-inch angles created a clear difference in ADD patterns. The tests also showed that a 1½-inch bridging member located 8 inches away vertically and offset a minimum of 2½ inches horizontally would not pose a significant challenge. See Figures 2A-C.

[5] Schwille, J. A., Kung, H.-C., Hjohlman, M., Laverick, G. E., & Gardell, G. W. (2005). Actual Delivered Density Fire Test Apparatus for Sprinklers Protecting High Commodity Storage. Fire Safety Science-Proceedings of the Eighth International Symposium, 823-833.

[6] Mammoser, J., & Kung, H.-C. (2007). The Evaluation of Early Suppression Fast Response Sprinkler Performance Obstructed by Bar Joist and Bridging Members in 40 foot High Buildings. Swiss Re Gaps and Pfizer, Inc. Underwriters Laboratories, Inc.



Figures 1A-C. ADD Obstruction Assembly for Bar Joist Depths of 22, 30, and 36 inches and a Horizontal Offset of 3 inches



Figures 2A-C. ADD Obstruction Assembly for Bridging Member
With Horizontal Offset of 2½ inches

3. Knowledge Gaps

The obstruction requirements found in current ESFR sprinkler standards were developed based upon limited testing. Because of this, assumptions and safety factors were used to provide an acceptable level of certainty that sprinklers would not be obstructed to the degree that would be detrimental to performance.

Since the development of the ESFR sprinkler system in 1987, ten full-scale fire tests were identified that examined the effect of a plugged or obstructed ESFR sprinkler. The tests focused on obstructions caused by bar joists and bridging members. Seven of these tests were conducted to push the boundaries of the obstruction limitations of ESFR sprinklers, with another three tests performed to examine the effect of a plugged sprinkler. All but two of the obstruction tests passed. The two tests that failed consisted of a bar joist (unknown depth) located 8 inches directly below the sprinkler and a bridging member (1½-inch angle) also located 8 inches directly below the sprinkler.

The ADD test series developed an ORF to quantify the effect of an obstruction on the ESFR sprinkler spray pattern. The ORF value was used to correlate if more or less water was collected in the pan, effectively showing a shadow or increase of water due to the obstruction. The series concluded with a set of scenarios that would be challenging or not so challenging to an ESFR sprinkler. It is worth noting the scenarios described as not challenging violate the existing ESFR sprinkler obstruction restrictions.

The ADD testing is limited to analyzing only the amount of water that is absorbed within the pans. The resolution was limited to 20-inch by 20-inch pans. It is unknown if the 400-square-inch pans provide adequate resolution.

The ADD tests are limited to testing the affect obstructions have on the spray pattern of the ESFR sprinkler. The tests do not incorporate the effect caused by water droplets deflecting off the obstruction or the fire plume carrying the droplets onto adjacent sprinklers and delaying the sprinkler activation. The result of the skipping phenomenon could cause excessive sprinklers to operate and the over taxing of the sprinkler system water supply or critical sprinklers to not operate because of the skipping. Other factors the ADD tests cannot validate in comparison to full-scale tests include pre-wetting of the commodities, water that is delivered through the aisles and flues to the outside surfaces of the array, and the entrainment of droplets into the fire. The results of the tests did provide evidence that existing obstruction limitations may be too conservative.

The previous studies have not compared the ADD results to the accepted RDD values. If the ADD values are greater than the RDD values, the assumption would be made that an ESFR sprinkler with the obstruction still provides the ADD required to achieve suppression. The assumption is made that the average ADD values (due to the size of the collections pans) are conducive to measuring the shielding effect of the obstruction.

The ESFR obstruction tests focused on the obstruction from a bar joist and from a bridging member between joists. These obstructions might create the most obvious conflict with the existing obstruction rules, but are not the only ones that designers and installers face. Additionally, they are more predictable which can facilitate coordination during the design process and minimize costly conflicts during construction.

Other obstructions include lights, plumbing fixtures, gas lines, electrical components such as cable trays and banks, ductwork, and for retail locations, signs and supporting members. Obstructions such as ducts, lights, and plumbing fixtures represent obstructions that are not square in shape and differ from obstructions that have been previously tested. The effect of the shape, materials, and other attributes of the obstructions are unknown. These obstructions are less predictable because they are typically installed in the field without drawings or review by the design team, which minimizes the ability to coordinate obstructions with the sprinkler installation. Discussions with fire sprinkler designers indicate these types of obstructions cause the most conflict.

The effect obstructions, other than joist and bridging members, would have on ESFR sprinkler performance has not been explored further than hypothetical situations. No literature was found on this topic.

Finally, a minimum clearance of 36 inches is required between the top of storage and ESFR sprinkler deflectors. This limits the ability to use ESFR sprinklers in situations where there is not sufficient clearance. The 36-inch distance is required to prevent water droplets from ricocheting off the top of storage and pre-wetting adjacent sprinklers[7]. Testing to substantiate this requirement was not found.

4. Experimental Test Plan

The full-scale testing will build upon the ADD testing of bar joist and bridging member obstructions completed by Mammoser & McCormick. The ADD testing provides a bench-scale method of assessing the relative significance of the effect of the obstructions on the fundamental sprinkler spray distribution. Comparison of the existing ADD testing data to the full-scale test results will provide a more pronounced understanding of the relationship between obstruction location and size within the ESFR sprinkler spray distribution. The results can be used to better understand a multitude of obstruction scenarios including miscellaneous obstructions.

The difference in the performance of the various ESFR sprinkler models needs to be understood such that the results of the testing program will not be product specific. ADD testing will be conducted, both with and without obstructions, to explore this issue. Twenty ADD tests are planned. From this work, the appropriate ESFR sprinkler model will be selected for use in the full scale testing. This data will also be compared to the Mammoser & McCormick data to measure the repeatability of the ADD testing.

Much thought was given to the parameters of the fire testing, especially sprinkler orifice size and ceiling height. Informal survey data was gathered for these two variables. Survey participants included NFPA 13 Discharge Committee members (manufacturers, consultants, regulators, insurance, and research organizations) and sprinkler designers from around the world. It was determine that storage warehouses constructed today commonly have a ceiling height of 40 feet.

[7] Based upon discussions with Dr. HC Kung, FM Global Research-retired.

Determining sprinkler orifice size was a more arduous task. Since the K-14 ESFR sprinkler has the smallest droplet size of the ESFR family, it is generally accepted that testing with a K-14 ESFR sprinkler is a worst-case condition because larger orifice ESFR sprinklers perform better. Additionally, the higher discharge pressure coupled with smaller droplet size could increase droplet ricochet affect compared to larger orifice sprinklers that have lower discharge pressures and larger droplets.

A recent change to NFPA 13 regarding use of K-14 ESFR sprinklers further complicates this issue. The provisions to use K-14 ESFR sprinklers to protect rack storage of Group A plastic commodity stored under a 40-foot ceiling have been removed from the 2013 Edition of NFPA 13. Testing showed that K-14 ESFR sprinklers performed in an unsatisfactory manner given a 40-foot ceiling height, with 20-foot storage of Standard Group A Plastic commodity, and ignition located between two sprinklers. One may argue the practicality of the high top of storage to ceiling clearance used in the test, but the use of the K-14 ESFR sprinkler in new warehouses with a ceiling height of 40 feet will nonetheless greatly decrease.

From the data compiled in the aforementioned survey, the use of K-14 sprinklers is also greatly decreasing due to the better performance and superior hydraulics of the larger orifice ESFR sprinklers. The K-17 sprinkler was determined to be the current most commonly used sprinkler. The K-17 sprinkler has the highest pressure and smallest droplet size of the ESFR sprinklers allowed or listed to protect 40-foot high buildings. The use of the K-17 sprinkler is considered the reasonable worst-case condition; therefore, allowing application of these results to the larger K factor ESFR sprinklers.

The legacy use of K-14 sprinklers deserves consideration. There are millions of these sprinklers protecting existing warehouses throughout the world. Assuming the useful life of a warehouse building is a minimum of 30 years, the use of the K-14 sprinkler will be relevant for years to come. The testing program will focus on the use of the K-17 ESFR sprinkler, but will exploit the K-17 sprinkler results to efficiently evaluate the K-14 sprinkler within its established parameters.

The full-scale testing will begin with double-row rack storage of Standard Group A Plastic commodity stored to a height of 30 feet with a 40-foot ceiling. Standard 6-inch transverse and longitudinal flue spaces will be provided at rack uprights and between unit loads. The sprinkler system will consist of K-17 ESFR sprinklers positioned at the ceiling with 14-inch clearance between the ceiling and the deflector. The sprinkler spacing will be 10 feet by 10 feet with an operating pressure of 52 psi. Ignition will be centered under one sprinkler, at the intersection of the transverse and longitudinal flue spaces. Standard igniters will be used. Specific igniter locations will be determined later.

The 10-foot clearance between the top of the storage and the ceiling with the ignition source located directly beneath a single ESFR sprinkler presents a greater challenge than with a lower clearance or the ignition source located between two ESFR sprinklers. The high ceiling clearance allows the fire plume to develop stronger before sprinkler activation. The upward velocity of the fire plume located directly underneath a sprinkler provides the worst-case scenario for the water spray distribution to penetrate the plume[8].

[8] Kung, H.-C., Vincent, B. G., Chan, T.-S., YU, H.-Z., & Stavrianidis, P. (1997). Early Suppression Fast Response (ESFR) Sprinkler Protection for 12m High Warehouses. International Association for Fire Safety Science (pp. 877 - 888). Melbourne, Australia: Fire Safety Science.

Use of the 40-foot ceiling and 30-foot storage coincides with survey data regarding most common ceiling height and is the highest storage array K-17 ESFR sprinklers can protect without rack sprinklers. The results of these tests will be applicable to lower ceiling and storage arrangements as well as larger orifice ESFR sprinklers.

The K-14 sprinkler will be tested by repeating the worst-case successful obstruction arrangement found during the K-17 testing. The storage array will be double-row rack storage of Standard Group-A Plastic commodity stored to a height of 25 feet beneath a 35-foot ceiling. This arrangement is the highest storage array K-14 sprinklers can protect without rack sprinklers. Standard 6-inch transverse and longitudinal flue spaces will be provided at rack uprights and between unit loads. The sprinkler system will be positioned at the ceiling with 14-inch clearance between the ceiling and the deflector. The sprinkler spacing will be 10 feet by 10 feet with an operating pressure of 75 psi. Ignition will be centered under one sprinkler, at the intersection of the transverse and longitudinal flue spaces. Standard igniters will be used. Specific igniter locations will be determined later.

The objective of better understanding the effect of obstructions on ESFR sprinkler spray distribution cannot be limited to obstruction caused solely by bar joist and bridging members. Comparison of the existing ADD testing data to the full-scale testing results will provide a more pronounced understanding of the relationship between obstruction location and size within the ESFR sprinkler spray distribution. The results can be used to better understand a multitude of obstruction scenarios. After the full-scale testing work, ADD testing will be conducted to explore the effect of these obstructions on ESFR performance. Full-scale testing will be used to validate sprinkler performance.

4.1. Full-Scale Test Series – Bar Joist Obstructions

Based on literature review and information provided by manufacturers of structural members, the depth of bar joists commonly used in warehouses is 30 inches, followed by 22 inches and 36 inches. For the 22-inch and 30-inch deep joists bottom chords consists of 2-inch by 2-inch double angles. The bottom chord of the 36-inch deep joist consists of 2½-inch by 2½-inch double angles.

The scenario with the bottom chord of the joist located directly underneath the sprinkler deflector (i.e., the sprinkler located within the web of the joist) was eliminated because the ADD testing resulted in an extremely challenging scenario. The data showed an ADD percentage reduction of 50 percent or greater for all three joist depths in the four center pans.

In order to establish parameters for obstructions, the initial test will consist of a joist depth of 22 inches with a horizontal offset of 3 inches. ADD data showed a consistent improvement in percent reduction of the ADD as the horizontal offsets increased and the joist depth increased as illustrated in Figure 3 and Figure 4. All sprinklers over the test array will be obstructed.

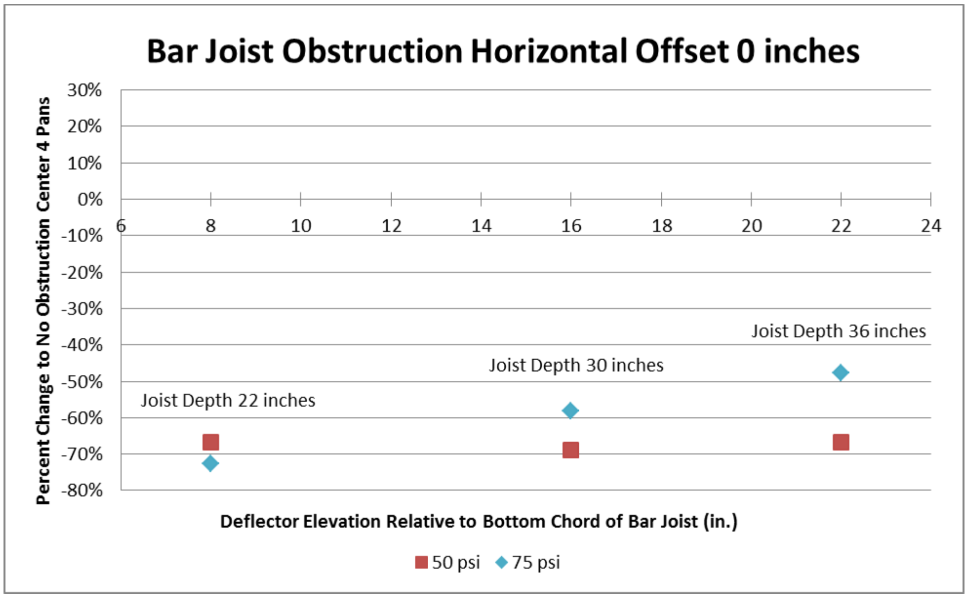


Figure 3. Bar Joist Obstruction with Offset of 0 inches

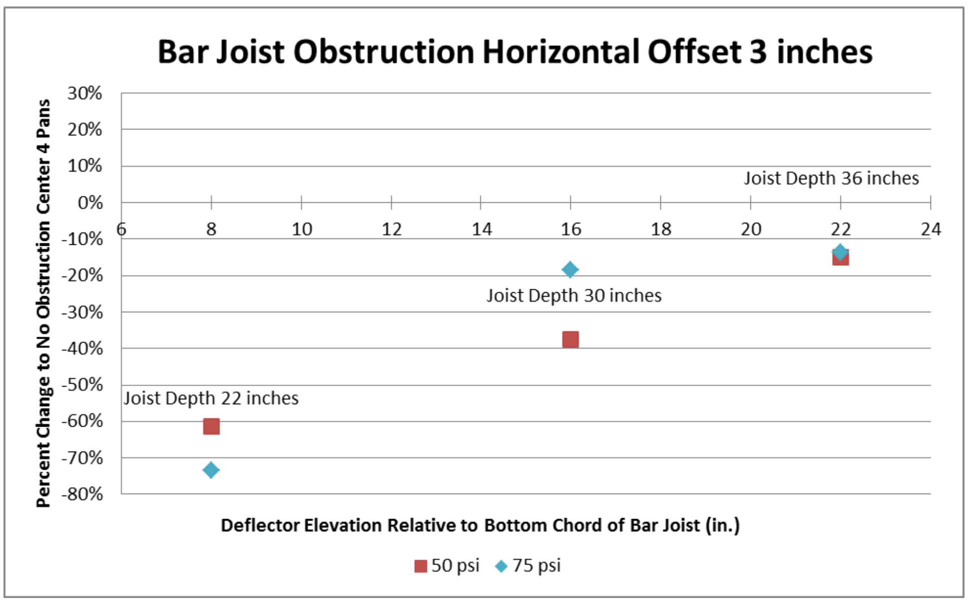


Figure 4. Bar Joist Obstruction with Offset of 3 inches

The result of Test 1 will determine the path of future tests. If Test 1 passes, the scenarios will include different joist depths with the same horizontal offset. If Test 1 fails, the horizontal offset will be increased to 6 inches followed by an increase in joist depth. Figure 5 shows a decision tree that outlines the testing plan based on the result of each test.

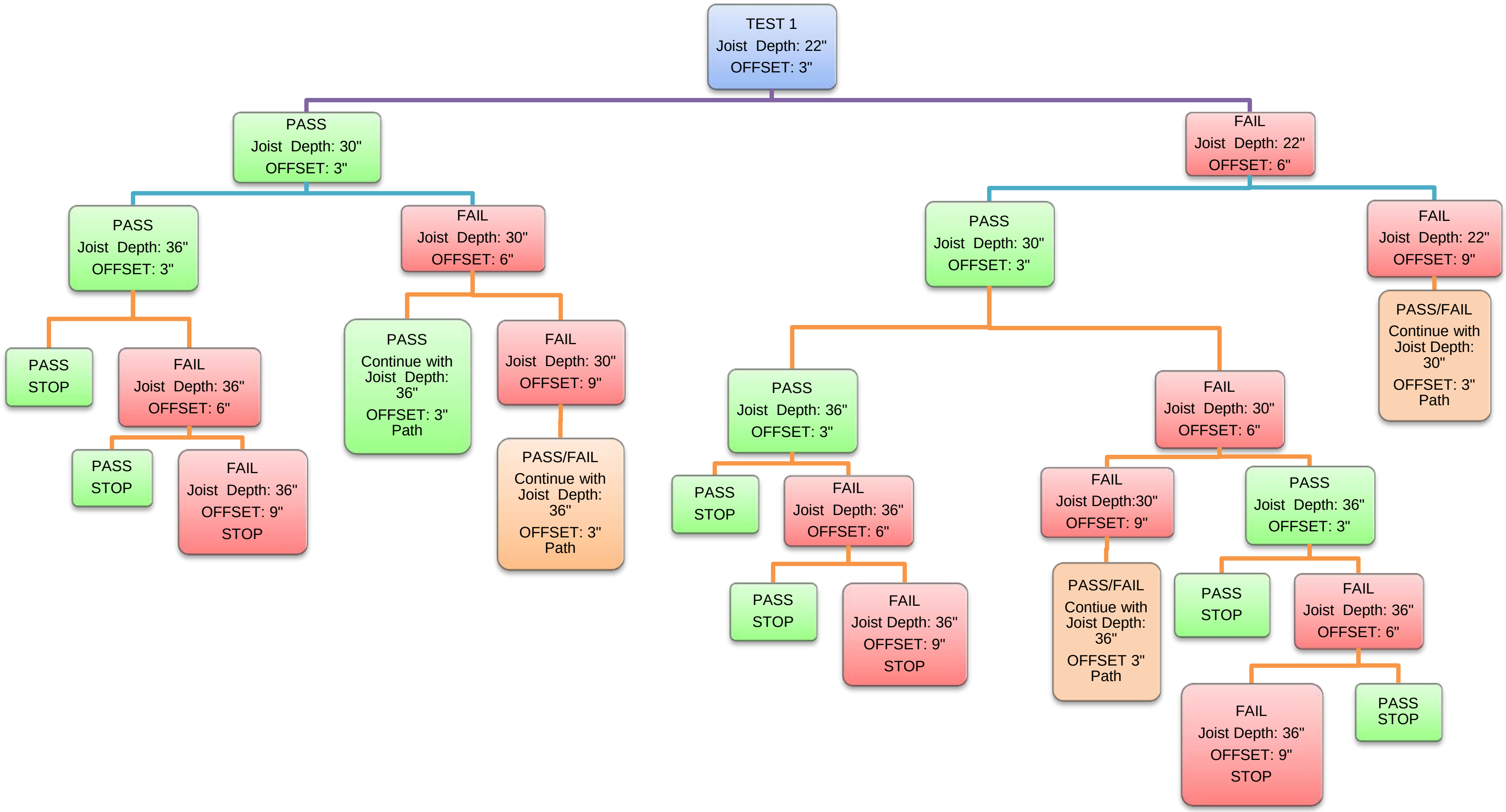


Figure 5. Bar Joist Obstruction Full-Scale Testing Decision Tree

4.2. Full-Scale Test Series – Bridging Member Obstructions

The bridging members will consist of 1½-inch by 1½-inch angles. The vertical offset distances of the bridging member to the sprinkler deflector used in the previously completed test series were 8, 16, and 22 inches, the proposed full-scale testing will locate the bridging members within the bar joist. The bridging members will be secured to the top of the double angles that make-up the bottom chord. This will cause the bridging member vertical offset from the sprinkler deflector to differ from the previous testing. For a 22-inch deep bar joist the vertical offset for the bridging member from the deflector will be 6 inches, for a 30-inch deep joist the vertical offset will be 14 inches, and a 36-inch deep joist will have a vertical offset of 19½ inches.

The results from the bar joist obstruction testing will dictate the testing arrangements of the bridging member. The most rigorous successful bar joist depth and offset will be used in the initial bridging member test arrangement. The bridging member will be located on the bar joist with variable offsets that increase if the test results in a failure.

The bridging members will have an initial offset from the sprinkler of 0 inches that can be increased to 3, 6, and 9 inches. After the 9-inch bridging member offset has been tested or the test results in a pass, the next bar joist depth will be used, until the bar joist depth of 36 inches is tested. If a 22-inch deep bar joist is selected, the initial bridging member offset will be 3 inches (the 0-inch offset will have been eliminated due to prior testing)[9].

4.3. Phase 2 – Miscellaneous Obstructions Test Series

Sprinkler designers and installers are challenged with obstructions other than supporting structural members. The Phase 2 testing series is meant to explore the effect of these obstructions. Examples include, but are not limited to, lights, plumbing piping, gas lines, cable trays, conduit banks, and ductwork. Building upon the results of the full-scale testing effort and the previously completed testing, ADD testing will be used to quantify the effect these obstructions have upon sprinkler discharge. The ADD testing will vary by obstruction width, horizontal offset, and vertical offset from the sprinkler deflector. Full-scale testing will be used to validate sprinkler performance. See Figure 6 for concept ADD assembly for miscellaneous obstructions.

[9] Previous full-scale testing reported by Vincent, B. G. [(1999). The Effect of Ceiling Bar Joist Obstruction Upon Suppression Performance of Early Suppression-Fast Response (ESFR) Sprinklers. NFPA Meeting. Factory Mutual Research Corporation] with the bridging member located 8 inches directly below the sprinkler deflector. See Table 1 Relevant ESFR Sprinkler Full-Scale Testing. ADD testing data done by U.L. resulting in a challenging scenario.

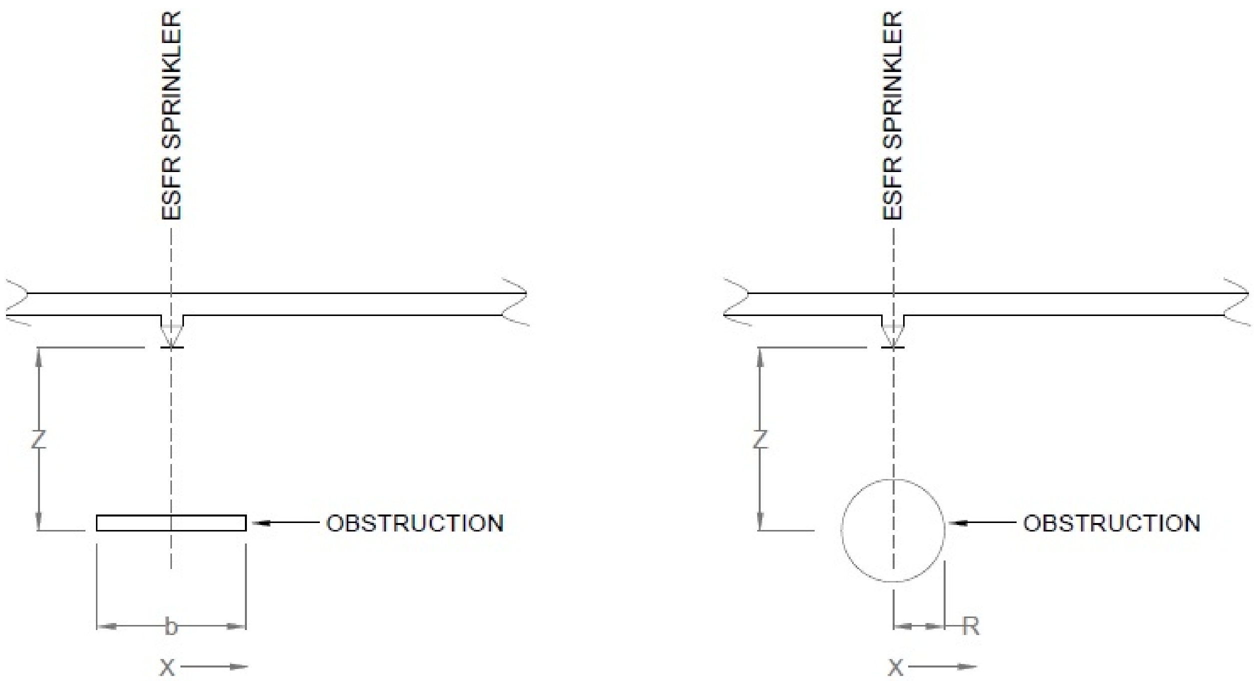


Figure 6. Concept ADD Assembly for Miscellaneous Obstructions

4.4. Phase 3 – Other Obstructions Test Series

Other obstructions challenges exist that are not covered in the proposed Phase 1 or 2 test series. The Phase 3 testing series is meant to explore these other obstruction challenges. The proposed obstruction challenges in Phase 3 will include:

- Obstruction placement under one, between two, and among four sprinklers.
- Grouped objects
- Multiple objects
- Vertical objects
- ESFR sprinklers located underneath obstructions

Building upon the results of the full-scale testing effort and the previously completed testing, ADD testing will be used to quantify the effect these obstructions have upon sprinkler discharge. Full-scale testing will be used to validate sprinkler performance.

5. Pass/Fail Criteria for Full-Scale ESFR Tests

The following pass/fail criteria were established:

1. A maximum of eight sprinklers activate – This is the same criterion established for K-22.4 ESFR sprinklers for similar ceiling/storage heights and provided a 50 percent safety factor assuming a 12-sprinkler design.

2. The fire is generally contained to the ignition array – The ignition array is defined as the center stacks, two pallet-loads long by two pallet-loads wide, of the main fuel array in which the igniters are located.

3. Ceiling gas temperatures are such that exposed structural steel would not be endangered (peak one minute average temperatures less than 1,000^{o}F) – This is consistent with all current ESFR sprinkler test criteria.

6. Conclusion

The objective of this research effort is to investigate the impact of obstructions on the performance of ESFR sprinklers. A literature search was conducted to mine available information so that past testing and other relevant research could be reviewed. The information found included limited full-scale testing and rather extensive ADD testing. From this effort, a testing plan was developed including quantifiable pass/fail criteria.

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7. Bibliography

Braggs, L. (2014, June 25). Sales Engineer, Vulcraft. (W. Fletcher, Interviewer)

Chan, T.-S. (1994). Measurements of Water Density and Drop Size Distributions of Selected ESFR Sprinklers. *Journal of Fire Protection Engineering*, 79 - 87.

Kung, H.-C. (1999). *"Fire Performance Evaluation of Viking K-14 Suppression Mode Upright Sprinklers.* Norwood, MA: Factory Mutual Research.

Kung, H.-C., Lee, J. L., & Yu, H.-Z. (1997). Suppression of Rack Storage Fires by Water. *International Association for Fire Safety Science* (pp. 901 - 912). Melbourne, Australia: Fire Safety Science.

Kung, H.-C., Lee, S., Ballard, R. J., & Moseley, M. W. (n.d.). Early Suppression of Rack Storage Fires with K363 Standard Response Sprinklers.

Kung, H.-C., Vincent, B. G., Chan, T.-S., YU, H.-Z., & Stavrianidis, P. (1997). Early Suppression Fast Response (ESFR) Sprinkler Protection for 12m High Warehouses. *International Association for Fire Safety Science* (pp. 877 - 888). Melbourne, Australia: Fire Safety Science.

Mammoser, J., & Kung, H.-C. (2007). *The Evaluation of Early Suppression Fast Response Sprinkler Performance Obstructed by Bar Joist and Bridging Members in 40 foot High Buildings.* Swiss Re Gaps and Pfizer, Inc. Underwriters Laboratories, Inc.

Mammoser, J., & McCormick, M. (2007). *Special Service Investigation of ADD tests with ESFR Sprinklers and Obstructions.* Swiss Re Gaps. Underwriters Laboratories, Inc.

Schwille, J. A., Kung, H.-C., Hjohlman, M., Laverick, G. E., & Gardell, G. W. (2005). Actual Delivered Density Fire Test Apparatus for Sprinklers Protecting High Commodity Storage. *Fire Safety Science-Proceedings of the Eighth International Symposium*, 823-833.

Vincent, B. G. (1999). The Effect of Ceiling Bar Joist Obstruction Upon Suppression Performance of Early Suppression-Fast Response (ESFR) Sprinklers. *NFPA Meeting.* Factory Mutual Research Corporation.

Yao, C. (1988). The Development of the ESFR Sprinkler System. *Fire Safety Journal, 14*, 66 - 73.

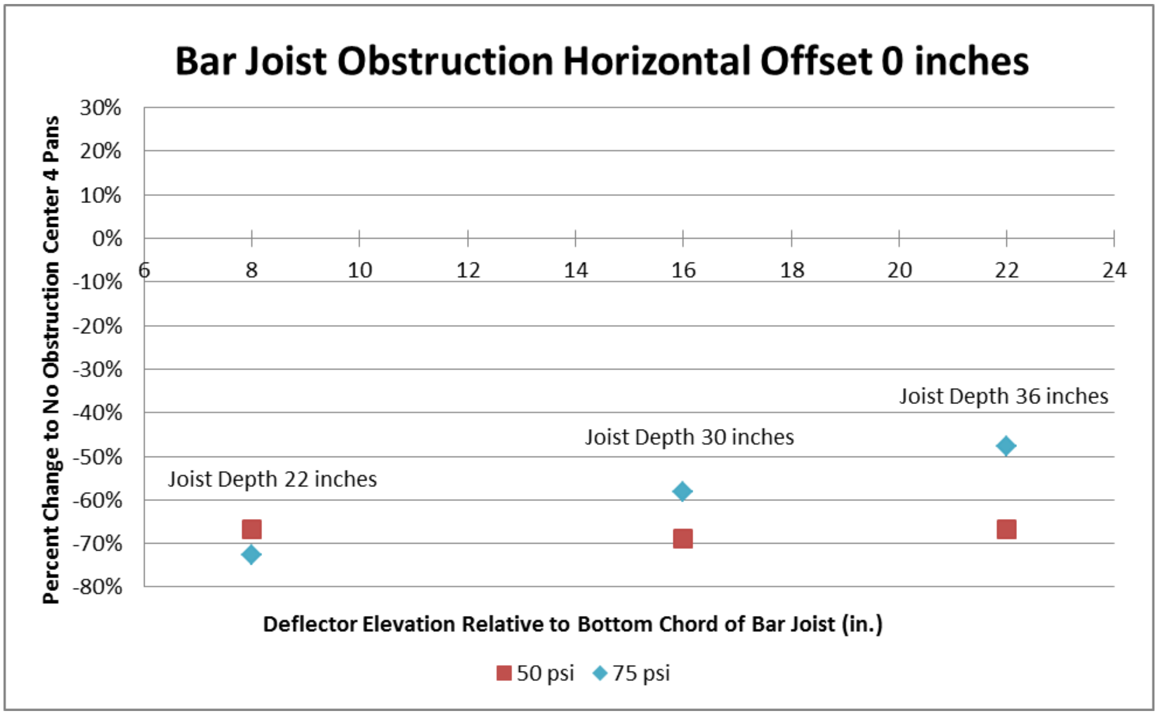
Yao, C. (1997). Overview of Sprinkler Technology Research. *Fire Safety Science - Proceeding of the Fifth International Symposium* (pp. 93 - 110). Melbourne, Australia: International Association for Fire Science.

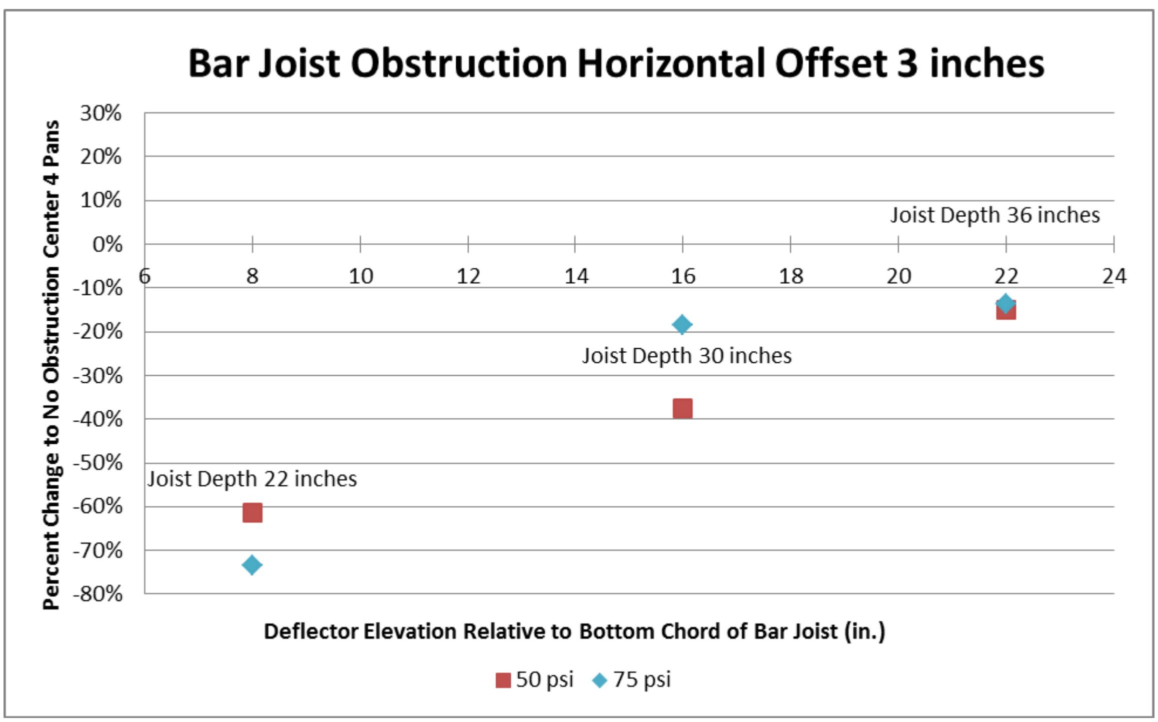
Yu, H.-Z. (2002). *Fire Performance Evaluation of K-16.8 Suppression Mode Upright Sprinklers.* Norwood, MA: Factory Mutual Insurance Company.

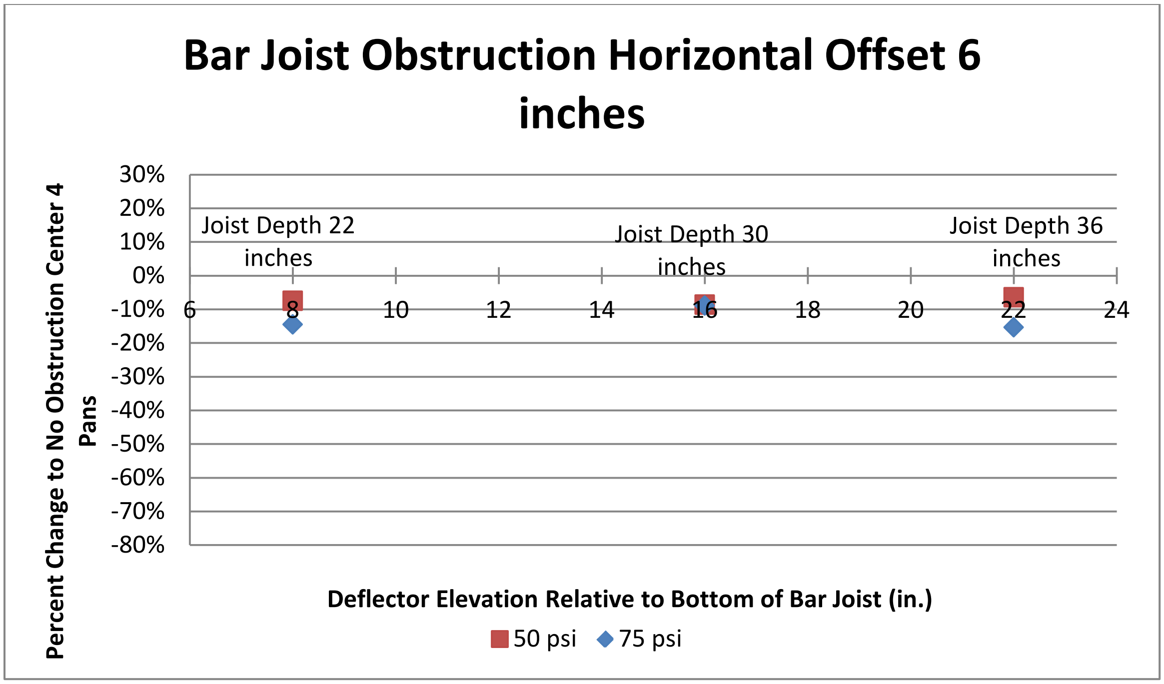
Appendix A – ADD Testing Data Summary

The graphs below demonstrate the relationship of the percent reduction in the ADD with Bar Joist and Bridging Members obstructions compared to ADD tests without obstructions. The information shown was provided from *Special Service Investigation of ADD Tests with ESFR Sprinklers and Obstructions*, Swiss Re Gaps and Underwriters Laboratories, Inc. authored by Mammoser, J., and McCormick, M.

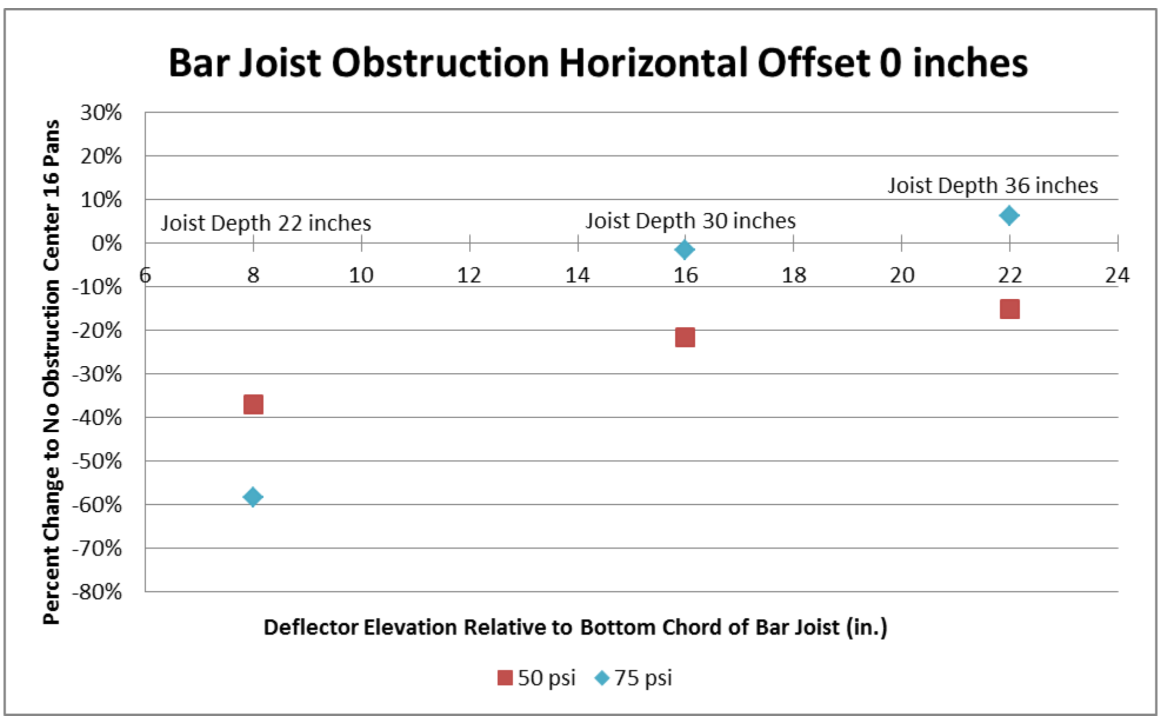
Bar Joist Obstructions Center 4 Pans:

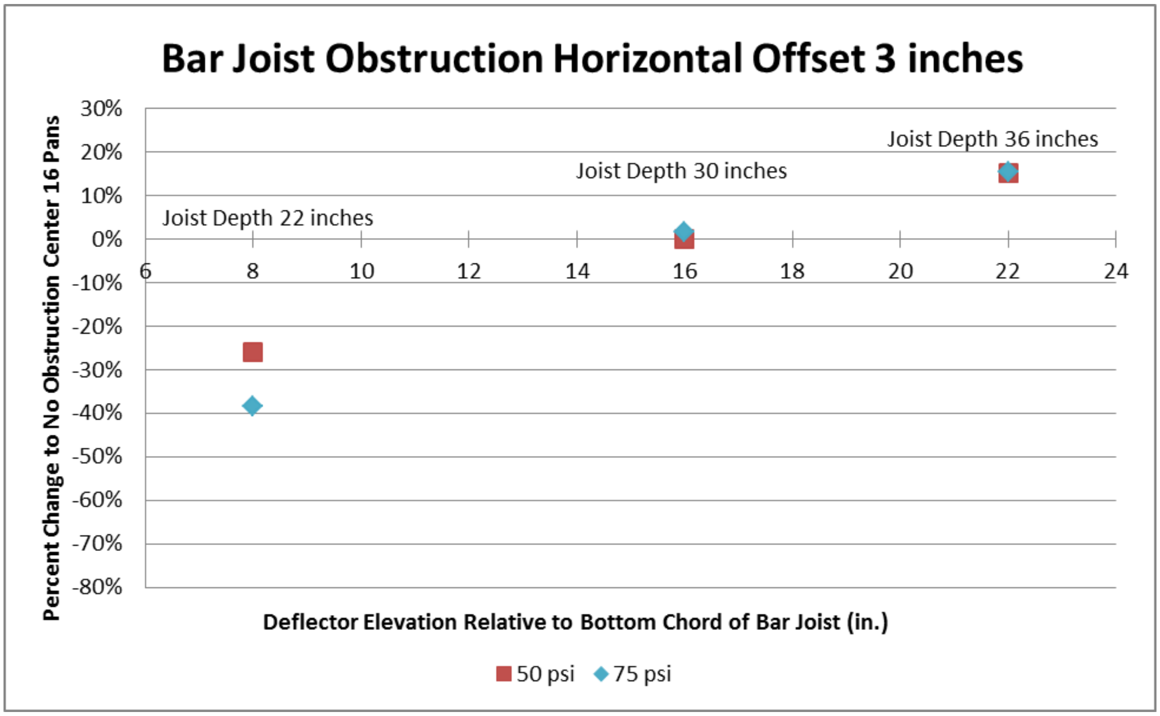


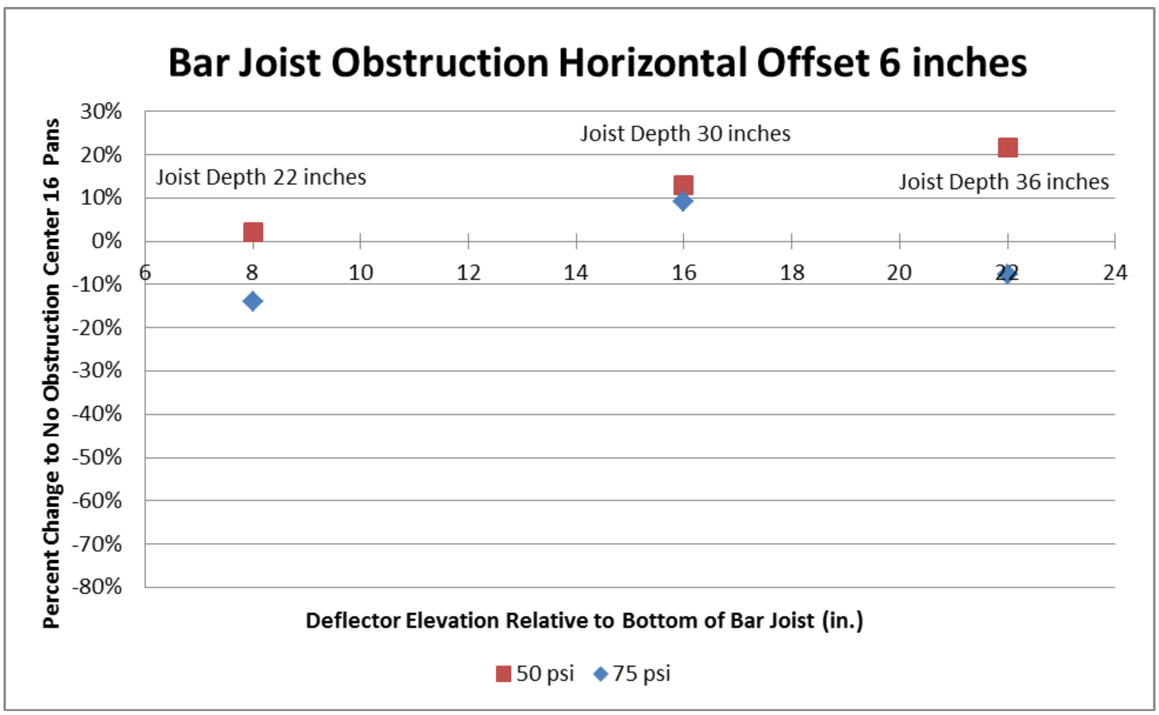




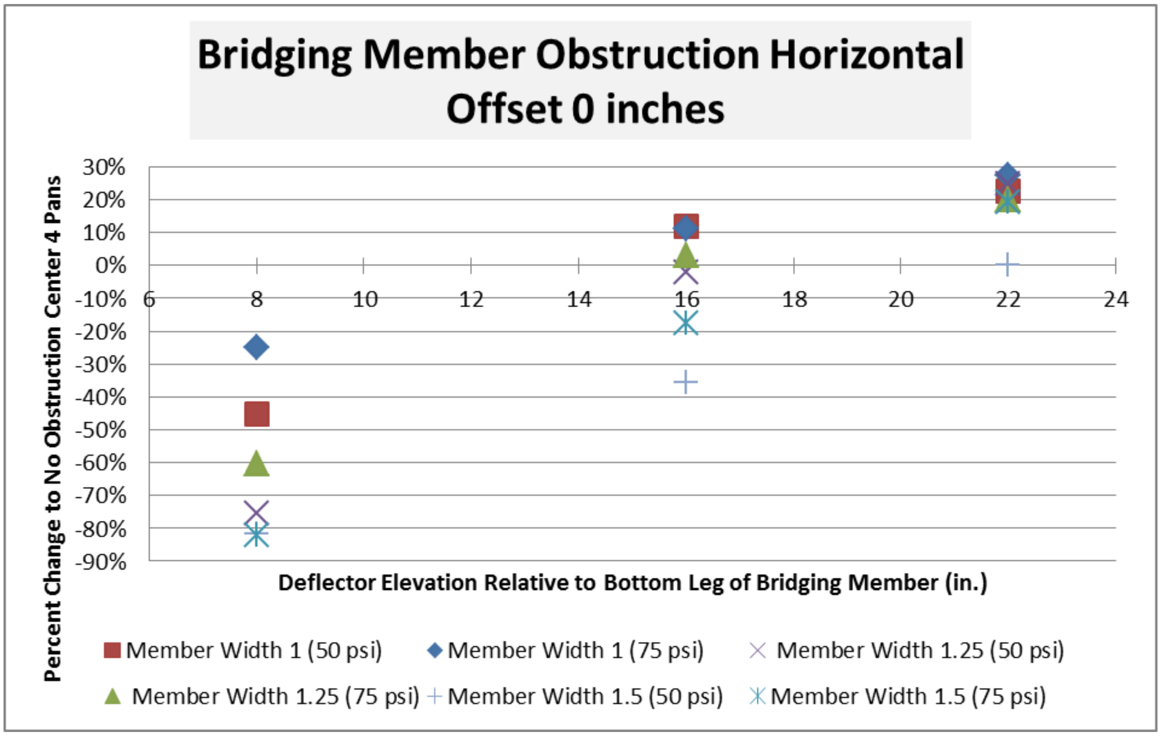
Bar Joist Obstructions Center 16 Pans:

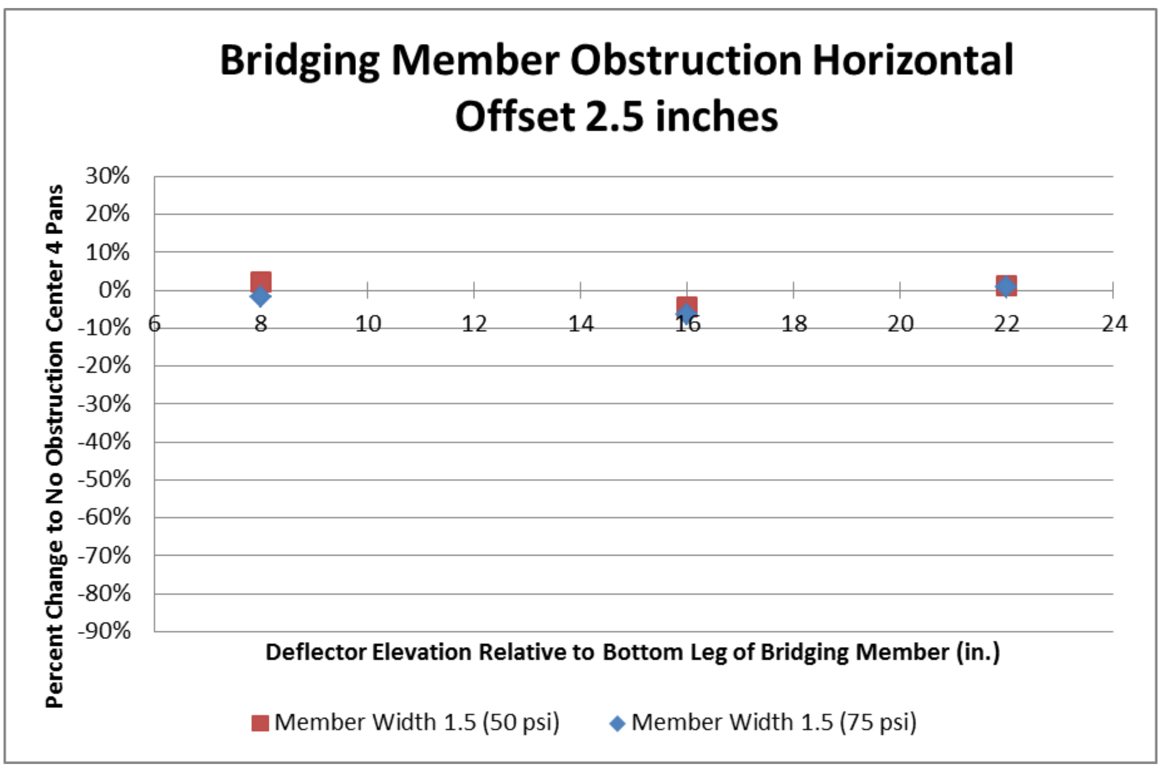


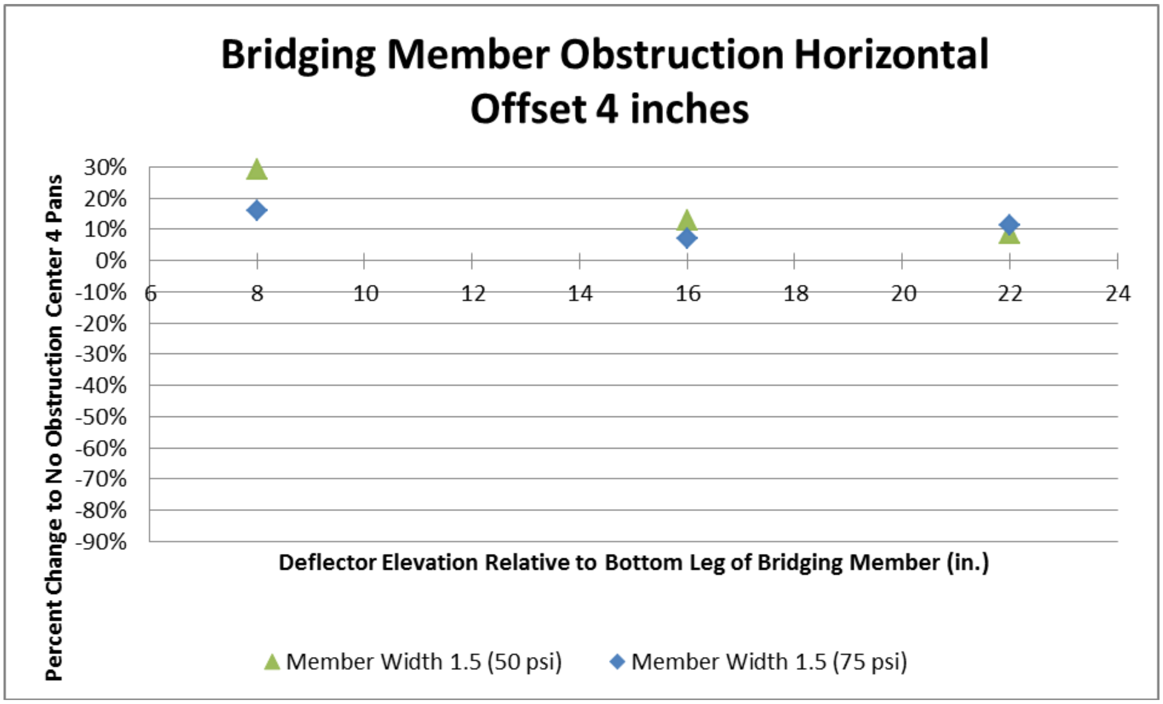

Bar Joist Obstruction Horizontal Offset 3 inches
Percent Change to No Obstruction Center 16 Pans
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
6
8
10
12
14
16
18
20
22
24
Joist Depth 22 inches
Joist Depth 30 inches
Joist Depth 36 inches
Deflector Elevation Relative to Bottom Chord of Bar Joist (in.)
50 psi
75 psi


Bar Joist Obstruction Horizontal Offset 6 inches
Percent Change to No Obstruction Center 16 Pans
30%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
6
8
10
12
14
16
18
20
22
24
Joist Depth 22 inches
Joist Depth 30 inches
Joist Depth 36 inches
Deflector Elevation Relative to Bottom of Bar Joist (in.)
50 psi
75 psi

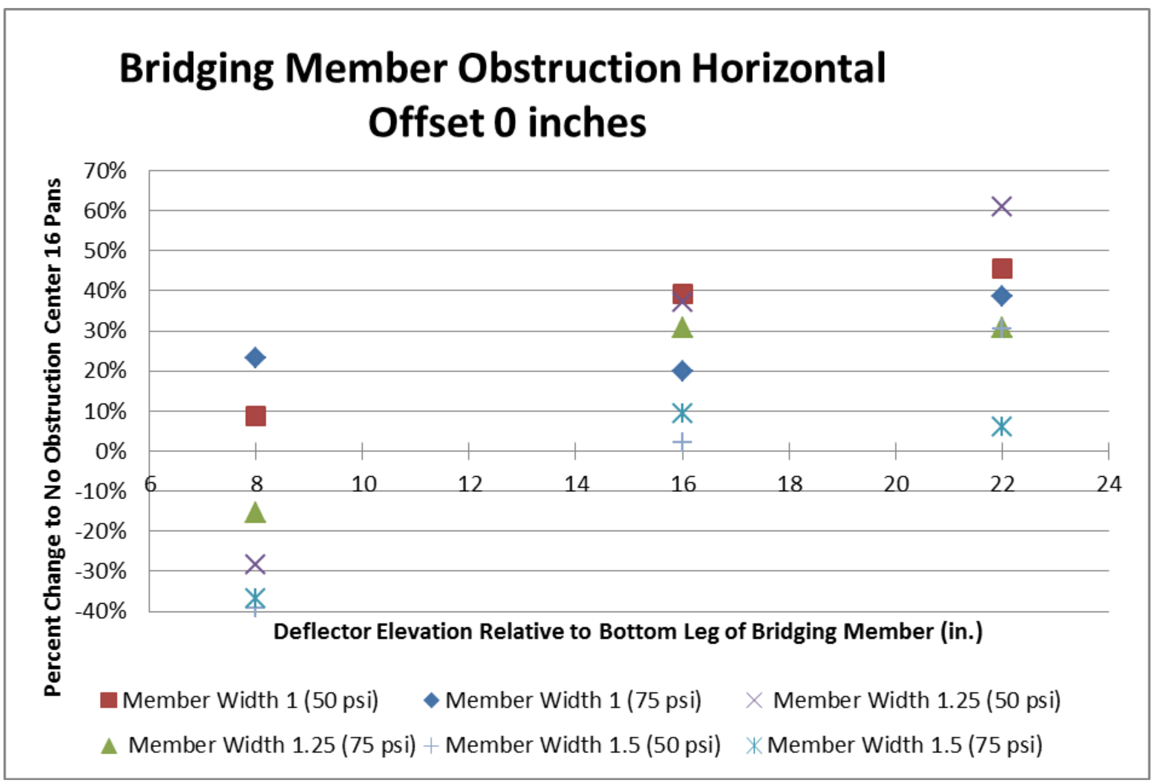
Bridging Members Obstructions Center 4 Pans:

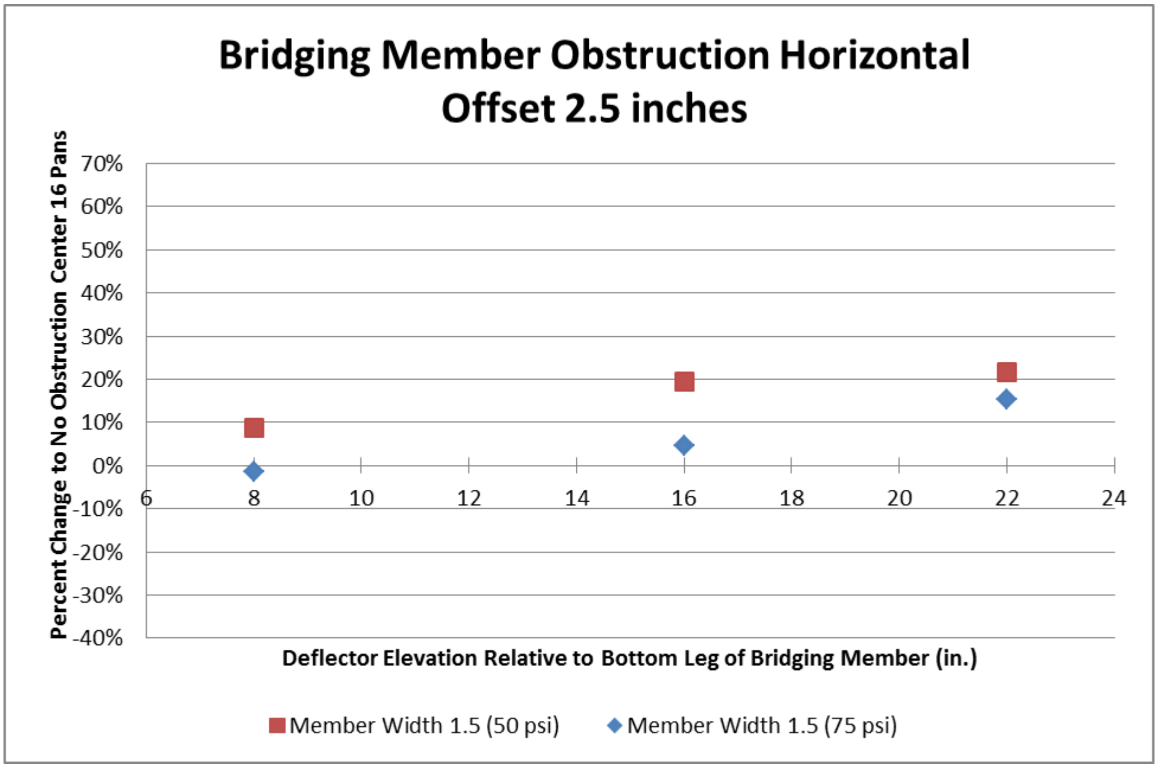


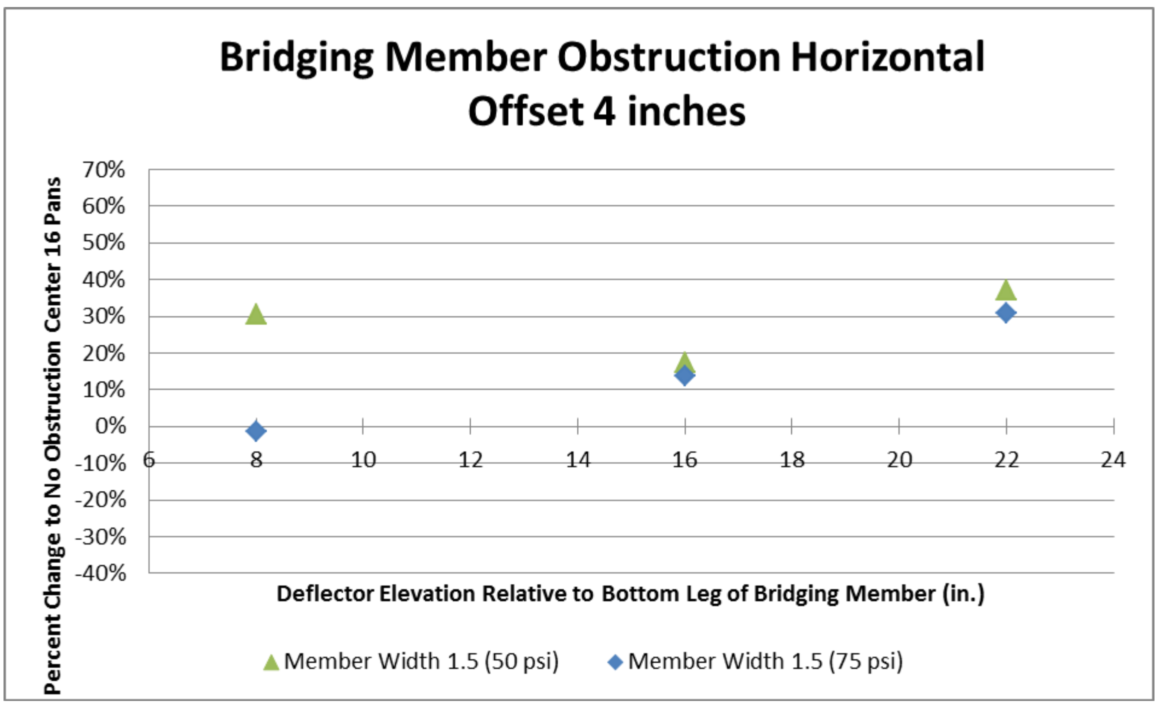




Bridging Members Obstructions Center 16 Pans:




Bridging Member Obstruction Horizontal Offset 2.5 inches
Percent Change to No Obstruction Center 16 Pans
70%
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
6
8
10
12
14
16
18
20
22
24
Deflector Elevation Relative to Bottom Leg of Bridging Member (in.)
Member Width 1.5 (50 psi)
Member Width 1.5 (75 psi)


Bridging Member Obstruction Horizontal Offset 4 inches
Percent Change to No Obstruction Center 16 Pans
70%
60%
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
6
8
10
12
14
16
18
20
22
24
Deflector Elevation Relative to Bottom Leg of Bridging Member (in.)
Member Width 1.5 (50 psi)
Member Width 1.5 (75 psi)