Protection of Storage Under Sloped Ceilings Phase III: Large Scale Testing Summary and Guidance

Final Report by:

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Foreword

There is limited prior research related to protection of storage under ceilings with slopes steeper than 2/12. Previous studies exist from FM Global, University of Maryland/Custom Spray Solutions, the Fire Protection Research Foundation, and National Fire Sprinkler Association (NFSA), but there are still many open questions related to the protection criteria for storage under sloped ceilings. The questions include, but not limited to, sprinkler activation pattern relative to fire source location, and optimal sprinkler installation orientation.

There are many different parameters related to this design challenge. Some of the key parameters include the slope of the ceiling, the commodity being stored, types of sprinklers (including ESFRs), sprinkler orientation, and sprinkler spacing. Some possible protection design solutions to sloped ceiling facilities are to use higher densities or larger calculation areas than for storage under flat ceilings.

Previous modeling efforts identified some of the potential protection challenges related to sloped ceilings and developed a plan for full scale testing. During this phase of the project, this full-scale test plan was implemented with the goal to determine the impact of sloped ceilings on protection of storage and develop the technical basis for new requirements and guidance in NFPA 13. This report provides a summary of the results from the full-scale testing along with protection recommendations.

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1.0 INTRODUCTION

There is currently limited guidance available on how to design fire sprinkler systems under sloped ceilings [1-5]. Large-scale suppression tests with sloped ceilings have not been readily available [6-7], and only a few small- and intermediate-scale suppression studies have been conducted [8-9]. The empirical evidence needed to develop suppression system design guidance did not exist.

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) “Protection of Storage Under Sloped Ceilings” project addresses the knowledge gaps on the impact of sloped ceilings on storage protection. Phase I [10-11] of the project involved a review of current storage configurations and numerical simulations of the effects of ceiling slope on suppression performance using the computational fluid dynamics (CFD) code FireFOAM [12-13]. The Phase I numerical modeling [11] investigated sprinkler activation and sprinkler spray patterns resulting from large-scale growing fires on a 3-tier-high rack storage array of the FM Global cartoned unexpanded plastic (CUP) commodity, equivalent to NFPA group A plastic commodity, under unobstructed ceilings of various slopes, ranging from a horizontal ceiling to a ceiling with an inclination of 33.7° (slope of 8 / 12). Ceiling clearances (between the top of the storage and the ceiling) of 3.0 m and 6.1 m (10 ft and 20 ft) were examined. In the sprinkler spray portion of the numerical modeling, a pendent, K-200 lpm/bar⁰.⁵ (K-14 gpm/psi⁰.⁵) sprinkler at 3.5 bar (50 psi) was considered, with the deflector in both the parallel-to-ceiling and parallel-to-floor orientations. The sprinkler orientation was changed based on the fact that NFPA specifies that the sprinkler be installed with the deflector parallel to the ceiling [1], while FM Global specifies that it be installed with the deflector parallel to the floor [2]. The simulations found that sprinkler activation times and patterns for quick-response, ordinary temperature (QR/OT) sprinklers for unobstructed ceilings ≤18° (slope of 4 / 12) inclination were similar to those for a horizontal ceiling for the four sprinklers immediately adjacent to the fire source. Activation delays that may have an adverse impact on protection design were found at ceiling inclination angles ≥26.6°. Spray simulations showed that the sprinkler deflector orientation, parallel-to-ceiling or parallel-to-floor, strongly affects the water flux that reaches the fire source, and that the parallel-to-floor orientation was preferable since it maintained a consistent water-flux distribution to the fire region irrespective of the ceiling inclination.

Phase II of the project consisted of laboratory characterization of sprinkler sprays and numerical modeling using FireFOAM that extended the work done in Phase I. Numerical simulations [14] evaluated sprinkler activation times and patterns in the presence of obstructed ceiling construction (purlins and girders), ridges and over a range of ceiling inclinations up to 18° (slope of 4 / 12). Additional spray simulations with an upright K-160 lpm/bar⁰.⁵ (K-11.2 gpm/psi⁰.⁵) and a pendent K-240 lpm/bar⁰.⁵ (K-16.8 gpm/psi⁰.⁵) sprinklers were also conducted. The spray simulations confirmed that the parallel-to-floor sprinkler orientation was preferable. The average activation times of QR/OT sprinklers with a ceiling inclination of 10° and purlin depths of 300 mm (12 in.), and a ceiling inclination of 18° and purlin depths of 100 mm (4 in.) were similar to those for horizontal ceilings for the same purlin depths. The presence of a ridge in sloped ceilings marginally affected the activation times of the four QR/OT sprinklers surrounding the ignition location, with activations near the ridge occurring slightly earlier on the near side of the ridge when the ridge was placed 6.1 m (20 ft) from the ceiling midpoint.
Analysis of the results from Phases I and II guided the development of the large-scale fire suppression test matrix. The Phase III test matrix was designed to address suppression performance effects from variations in ceiling slope, purlin and girder arrangements, and sprinkler deflector orientation. This report summarizes the large-scale testing that was conducted at FM Global with the intent of providing pointed guidance on storage protection under sloped ceilings to the NFPA 13 technical committee.

2.0 LARGE SCALE TESTING OBSERVATIONS & SUMMARY

FRA observed portions of the large-scale experimental testing program conducted by FM Global and reviewed the testing report [16].

2.1 Overview

Seven large-scale sloped ceiling tests were conducted at the Large Burn Laboratory in the FM Global Research Campus, West Glocester, RI. Tests were conducted with a 4-tier-high rack storage of the CUP commodity under the sloped ceiling, Table 1. The storage configuration was a double row, open frame rack main array with single row open frame target arrays. Ignition for all tests was offset among four sprinklers, Figure 1. Various obstructed ceiling construction configurations in the form of purlins and girders were tested. The basic test configuration is shown in Figure 1. For comparison a baseline non-sloped unobstructed ceiling test was also performed. The baseline test consisted of 6.1 m (20 ft) high open double-row rack storage of CUP under a 9.1 m (30 ft) high ceiling with 1.2 m (4 ft) wide aisles separating the main array from the two target arrays. Sprinkler protection was provided by 74°C (165°F) rated, quick-response K-240 (K-16.8) pendent ESFR sprinklers installed on 3.0 x 3.0 m (10 x 10 ft) spacing and arranged to provide a constant pressure of 2.4 bar (35 psi) for each operating sprinkler. The main rack was centered among four sprinklers and ignition was offset 0.61 m (2 ft) toward the east (see Figure 1). A total of three sprinklers operated and provided fire control.

One sloped ceiling test was conducted in the absence of purlins and girders (i.e., unobstructed, sloped ceiling), with the remaining six tests conducted with obstructed ceiling construction. The obstructed ceiling construction consisted of sheet metal purlins having a depth of either 300 mm (12 in.) or 460 mm (18 in.), whereas the sheet metal girders were 610 mm (24 in.) deep for all test conditions. Specifications of the girder/purlin spacing and construction are provided Figure 1 and additional details on the construction may be found in FM Global Technical Report 3059743 [16].

In Phase II of the project the impact of ceiling slope was found to be somewhat mitigated by the ceiling obstructed construction, however the purlins can result in flow channeling (confinement of flow within the deep channels formed by the purlins) which could cause additional sprinkler activations away from the fire. In several of the large-scale tests the purlin channels were, therefore, closed at the girder location to evaluate the impact on sprinkler activations.

2.2 Test Criteria

Ideally the presence of a sloped or obstructed ceiling construction should not impact sprinkler activation times or suppression performance when compared to the results of large-scale tests conducted under non-sloped, unobstructed ceiling construction. Thus, the evaluation criteria focuses on examining the differences in performance that are observed when a sloped and
obstructed ceiling is introduced. Four primary characteristics were considered for determining test success.

- Total sprinkler activations should remain nominally the same as the baseline test.
- Sprinkler’s located along the perimeter of the lab test ceiling ideally should not activate, as activation indicates that there is a probability that additional sprinklers beyond the perimeter sprinkler would activate had the ceiling structure been larger. If a perimeter sprinkler did not activate then there is confidence that no additional sprinklers would open.
- Fire spread and damage should be nominally the same as the baseline test. In addition, the fire should not spread to the backside of the target arrays or to the ends of the main array.
- Lastly the observed structural steel temperatures should be nominally the same as the baseline test and should not exceed 538°C (1000°F).

Based on these criteria, the relative success of a test could be evaluated, and subsequent guidance developed.

![Figure 1: Plan view of the test setup showing the general arrangement of the storage, sprinkler, ignition, and the obstructed ceiling construction arrangement. Modified with permission [15].](image)

2.3 Test Results: Baseline

During the baseline test, as shown in Figure 2, the 1st sprinkler operated 82 seconds after ignition quickly followed by two more sprinklers operating 1 and 3 seconds after the activation of the 1st sprinkler. The fire was quickly suppressed and did not travel to the ends of the main array or jump
the aisle to either of the target arrays. The test was concluded at 25 minutes and post-fire observation of the damage showed limited spread around the ignition location, Figure 2. The results of the baseline test demonstrate that the sprinkler protection installed at ceiling level is capable of limiting sprinkler operations to the first ring of sprinklers. Therefore, subsequent testing that results in sprinkler operations beyond the first ring would suggest that the varied parameters could have an influence on the performance of the sprinkler system. Under such conditions, the sprinkler system design obtained from the baseline test may need to be modified to account for the given parameter condition (i.e. sloped ceiling, obstructed ceiling construction, or both).

![Figure 2: Baseline damage assessment. (a) Top view, (b) West face of main array, (c) East face of main array. Used with permission from FM Global. © 2019 FM Global [16].]
2.4 Sloped Ceiling

Seven sloped ceiling tests were conducted at two different ceiling slopes with various obstruction criteria as summarized in Table 1. The storage array was offset from the center of the ceiling to allow for more sprinklers to be located on the upslope of the ceiling to continue the exploration of skewed sprinkler activation patterns toward the upslope. A brief summary of the test configurations is presented in Table 2 with full details and discussion presented in FM Global Technical Report 3059743 [16]. For each of the sloped ceiling configurations the sprinkler deflector was located 150 mm (6 in) from the bottom of the purlins in order to (1) place it in an ideal location for heat plume exposure, and (2) to avoid obstruction to the sprinkler’s discharge pattern. This standoff distance (i.e. the vertical distance between the sprinkler’s deflector and an adjacent object, such as the ceiling or the bottom edge of a purlin or girder) was previously shown [11, 14] to be acceptable based on numerical modeling which demonstrated that standoff distances up to 150 mm (6 in) did not adversely affect sprinkler activation times, though the distance exceeds the recommendations provided in NFPA 13 [1] and DS 2-0 [2].

<table>
<thead>
<tr>
<th>Storage Configuration</th>
<th>4-tier high rack storage of CUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling Inclination</td>
<td>10°, 18°</td>
</tr>
<tr>
<td>Ceiling Clearance</td>
<td>3 m (10 ft) from top of the main array’s longitudinal flue</td>
</tr>
<tr>
<td>Purlin Depth</td>
<td>300 mm (12 in.), 460 mm (18 in.)</td>
</tr>
<tr>
<td>Purlin Spacing</td>
<td>1.5 m (5 ft)</td>
</tr>
<tr>
<td>Girder Depth</td>
<td>610 mm (24 in.)</td>
</tr>
<tr>
<td>Girder Spacing</td>
<td>7.6 m (25 ft), 12.2 m (40 ft)</td>
</tr>
<tr>
<td>Sprinklers</td>
<td>K-240 (K-16.8) pendent, quick response sprinklers with link temperature of 74°C (165°F) spaced at 3 m x 3 m (10 ft x 10 ft)</td>
</tr>
</tbody>
</table>

2.5 Test Results: 10° Inclination

Four tests were conducted at the 10° ceiling inclination in which the purlin depth, closing of the purlin channels, girder spacing, sprinkler deflector distance, and sprinkler orientation were changed. Tests 3 and 4 had 300 mm (12 in.) purlins spaced 1.5 m (5 ft) apart and were identical with the exception of the sprinkler deflector orientation: Test 3 was conducted with the deflectors parallel to the floor while Test 4 used the parallel to the ceiling orientation. While both orientations performed nominally the same and produced acceptable results, which the numerical simulations suggested would be the case for an among four sprinkler ignition scenario, a few observations were made that would be more concerning at increased slopes. Most notably the spray central core was angled away from the intended region when the sprinkler was oriented parallel to the ceiling which resulted in significantly higher overall energy release and greater amount of commodity was consumed. A similar behavior of the spray core moving toward the upslope was observed in the spray simulations [11, 14, 17]. In Test 4, this shifting of the core resulted in water delivery to the upslope target array instead of the main array and resulted in elevated ceiling jet temperatures when compared to the parallel to the floor orientation. While the performance of each scenario was acceptable, these issues could be further enhanced with changes to the configuration, namely the slope, increased storage height, or ignition location. Thus, while the outcomes were acceptable
for both the tests, the trends of the results strongly indicate that a parallel to the floor orientation would be beneficial for all slopes.

Tests 5 and 6 had 450 mm (18 in.) purlins spaced 1.5 m (5 ft) apart and were similar in most respects but altered the girder separation distance with the girders spaced at 7.5 m (25 ft) for Test 5 and 12 m (40 ft) for Test 6. In both tests, the purlin channels were closed at the girder locations. During Test 5 the spray was observed to have been obstructed by the girder placement and this significantly affected the outcome, with the fire spreading the length of the main array and jumping the aisle. With the fire reaching one end of the main array it could be expected that had the array been longer in length, the fire could have spread further. Test 6, in which the sprinkler was obstructed, did not have any spray obstructed, resulting in less damage to the commodity, and the fire did not spread to the end of the array or jump the aisle. Test 5 and 6 illustrate the importance of not obstructing the sprinkler spray. With the exception of Test 5, in which the sprinkler discharge was obstructed by the girder, the pass/fail criteria for each of the tests was satisfied with the number of sprinklers operating ranging between 4 and 7. Thus, for ceiling configurations with inclinations of 10⁰ or less, open purlin channels, and a purlin depth up to 300 mm (12 in.) the outcome was acceptable though additional sprinkler activations occurred. For purlin depths over 300 mm (12 in.) and up to 450 mm (18 in.), similar performance was observed, however it required the closing of the open gaps above the girders in order to reduce the channeling effect of the heat plume within the purlins and thus limit the number of sprinkler operations remote from the ignition location. In all cases it should be emphasized that the sprinkler installation, including their spacing, should be such that obstruction of the spray will not occur, otherwise the protection design will be impaired.

2.6 Test Results: 18⁰ Slope

Three tests were conducted with an 18⁰ slope with similar configuration changes as the 10⁰ configuration. A summary of the test specifics and results are provided in Table 2. Test 1 modified the baseline test by introducing a slope but did not have any purlins or girders present, while Tests 2 and 7 included an obstructed ceiling configuration. Test 1 resulted in approximately the same damage area as the baseline, however it did result in ten sprinkler activations, seven additional sprinkler activations above the baseline. The increased sprinkler activations would require higher overall flow which the system would need to be able to provide in order to adequately protect the specific storage configuration.

The set-up for Test 2 was similar to that of Test 1, however the ceiling included 450 mm (18 in.) girders and 300 mm (12 in.) deep purlins. While the pass/fail criteria was acceptable, excessive channeling of the heat plume throughout the length of the purlin channels was observed. The test resulted in the operation 13 sprinklers, 10 additional sprinklers above the baseline. Not only did sprinklers in the second ring operate, but several sprinklers in the third ring operated as well.

The Test 7 ceiling configuration differed from Test 2 in that (1) the horizontal distance between girders was increased from 7.6 m (25 ft) to 12.2 m (40 ft), and (2) the purlin channels above the girders was closed. While the pass/fail criterion was acceptable, a total of 7 sprinklers operated, 4 additional over that observed in the baseline test. Sprinklers in both the first and second ring operated.
Table 2: Summary of test configurations and test results. [16]

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Test 6</th>
<th>Test 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (degrees)</td>
<td>0</td>
<td>18</td>
<td>18</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Deflector Orientation</td>
<td>Floor</td>
<td>Floor</td>
<td>Floor</td>
<td>Floor</td>
<td>Ceiling</td>
<td>Floor</td>
<td>Floor</td>
<td>Floor</td>
</tr>
<tr>
<td>Deflector Distance from Ceiling mm (in)</td>
<td>330 (13)</td>
<td>330 (13)</td>
<td>460 (18)</td>
<td>460 (18)</td>
<td>460 (18)</td>
<td>610 (24)</td>
<td>610 (24)</td>
<td>460 (18)</td>
</tr>
<tr>
<td>Purlin Depth mm (in)</td>
<td>-</td>
<td>-</td>
<td>300 (12)</td>
<td>300 (12)</td>
<td>300 (12)</td>
<td>450 (18)</td>
<td>450 (18)</td>
<td>300 (12)</td>
</tr>
<tr>
<td>Purlin Channels Open/Closed</td>
<td>-</td>
<td>-</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
</tr>
<tr>
<td>Girder Depth mm (in)</td>
<td>-</td>
<td>-</td>
<td>600 (24)</td>
<td>600 (24)</td>
<td>600 (24)</td>
<td>600 (24)</td>
<td>600 (24)</td>
<td>600 (24)</td>
</tr>
<tr>
<td>First Sprinkler Operation (s)</td>
<td>82</td>
<td>78</td>
<td>74</td>
<td>82</td>
<td>76</td>
<td>97</td>
<td>83</td>
<td>73</td>
</tr>
<tr>
<td>Last Sprinkler Operation (s)</td>
<td>85</td>
<td>210</td>
<td>186</td>
<td>101</td>
<td>152</td>
<td>647</td>
<td>94</td>
<td>233</td>
</tr>
<tr>
<td>Total # Sprinkler Operations</td>
<td>3</td>
<td>10</td>
<td>13</td>
<td>6</td>
<td>4</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Perimeter Sprinkler Operations</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Fire to Ends of main Array</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Aisle Jump</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
3.0 SUMMARY & GUIDANCE

3.1 Summary

As was demonstrated in Phase I and II of research [10-11, 14-15], there is currently a lack of clear guidance on how to design fire sprinkler systems for storage protection below sloped ceilings. The test series summarized here provides new information pertaining to the effect of sloped ceilings and sprinkler installation orientations on suppression performance using K-240 (K-16.8) early suppression, fast response (ESFR) type sprinklers. From the testing conducted, several key observations can be made:

For 10º ceiling inclination and the specific test configurations explored,

1. The sprinkler arrangement was sufficient to protect the standard CUP commodity when the spray was not obstructed (Test 5). FM Global Data Sheet 2-0, *Installation Guidelines for Automatic Sprinklers* presently includes recommendations on ensuring that ceiling obstructions do not interfere with the spray discharge pattern.

2. With the exception of Test 5, the pass/fail criteria for each of the tests was satisfied with the number of sprinklers operating ranging between 4 and 7, and additional 1-4 activations when compared to the results of the baseline test.

For 18º ceiling inclination and the specific test configurations explored,

1. The sprinkler arrangement was sufficient to protect the standard CUP commodity.

2. The pass/fail criteria for each of the tests was satisfied with the number of sprinklers operating ranging between 7 and 13, an additional 4-10 activations when compared to the results of the baseline test.

General observations:

1. The impact of ceiling inclination is evident from the comparison of the 10º and 18º slopes as the 10º inclination resulted in a number of sprinkler activations similar to the baseline while the 18º slope resulted in significantly more additional activations.

2. When the purlin channels are closed at 12.2 m (40 ft), ceiling jet channeling within the purlins is reduced, and activations beyond the girders was not observed.

3. While the sprinkler deflector orientation had limited impact on the test outcomes for Tests 3 and 4 with the ignition location in an among four sprinkler scenario, it was clear that the spray core was shifted from its intended area of application and that for ceiling slopes greater than 10º a parallel to the floor deflector orientation would be more appropriate based on numerical modeling [10-11, 14] and cold flow spray testing [17]. Additionally, the measured ceiling jet temperatures and the overall energy release rate were higher compared to the test conducted with the parallel to the floor orientation.

4. Girder and purlin spacing with regards to sprinkler location is critical and it needs to be ensured that their presence will not interfere with the spray distribution. Additionally, sprinkler deflectors should be located on a plane no more than 150 mm (6 in.) below the obstructed construction.

5. While testing conducted was limited to a selected few storage conditions (e.g., commodity type, storage and ceiling heights), it is expected that the results will be applicable to other
similar arrangements and that in general if the configuration (storage height, commodity, etc.) is similar to the test conditions, then the outcomes would be similar. If the storage configuration, protection scheme, or other conditions are varied from those tested, case specific analysis is recommended to support the design.

### 3.2 Guidance

The guidance presented is based on the results of the Phases I-III research which included CFD modeling, spray characterizations and cold flow testing, and a large-scale test series. While the conclusions and guidance are tied specifically to the test configurations explored, a 4-tier-high CUP rack storage configuration, the results are expected to be more broadly applicable to similar configurations. The observations and conclusions from the Phases I-III studies yield the following guidance:

1. Sprinkler deflector orientation should be arranged parallel to the floor to avoid a significant reduction in the water flux available to the ignition region. This is especially true for ceiling slopes in excess of 10º and should be considered for all other slopes as well.

2. When sprinklers are to be installed below the bottoms of the ceiling structural support members, such as purlins, the sprinkler deflector should be oriented with the deflectors on a horizontal plane no more than 150 mm (6 in.) below the underside of the structural support member. For ceiling inclinations up to 10º, purlin depths should be limited to 450 mm (18 in.). For ceiling inclinations between 10º and 18º purlin depths should be limited to 300 mm (12 in.).

3. For (1) ceiling slopes up to 10º with purlin depths greater than 300 mm (12 in.), or (2) ceiling slopes over 10º purlin channels should be closed at the girder to prevent excessive ceiling jet channeling.

4. For slopes in excess of 18º, and for all purlin depths, the installation of sprinklers at their normal listed spacing on a horizontal plane below the structural support members is not recommended. For these ceiling slopes alternative options including in-rack sprinklers and/or a false-/drop-ceiling with sprinklers installed below it will need to be explored.

5. Alternative sprinkler spacing options should ensure that there is no obstruction to the discharge pattern from the obstructed ceiling construction, when present.
4.0 SUPPLEMENTAL INFORMATION: SLOPED CEILING – ACTIVATION TIMES FOR FIRE UNDER A GIRDER

During the course of this project the FPRF technical panel discussed the scenario in which a fire occurred directly beneath a ceiling girder. A concern was raised that a fire in this location may result in changes to the activation pattern of sprinklers due to the development of a ceiling jet in the purlin channels on either side of the girder. The panel indicated that should this occur that additional sprinkler activations could occur which may impact the water demand.

To address this concern FM Global carried out a series of simulations to examine sprinkler activation times and patterns for comparison with previously reported results. While this report does not provide details on the simulations [20], a summary of the conclusions reached from the analysis is provided below.

- “On average, sprinkler activation times in the first and second rings are not significantly affected when the fire is under a girder compared to when the fire originates between two girders.”
- “Average activation times compared to fire between girders scenarios is found to differ by less than 10 s. Also, compared to unobstructed, non-sloped ceiling, the activations are earlier.”
- “Closing the purlin channels ensures activation of sprinklers far away along the channels is delayed, an effect also observed in previous simulations with fire originating between girders [11] and confirmed by large-scale testing [21].”
- “Girder width is found to have a minor effect on activation times.”

Based on the above it can be concluded that a fire occurring under a girder is not a concern with regard to additional sprinkler activations. Furthermore, a fire under a girder did not result in ceiling jet development at greater distances when compared to fire between girders. As a result of the analysis the conclusions and recommendations for obstructed, sloped ceilings determined from previous simulations and large-scale testing [11,21] should apply to scenarios where the fire originates under a girder. [20]
5.0 REFERENCES


[20] Chatterjee, P., Sloped ceiling – activation times for fire under a girder, FM Global Technical Memorandum, August 20, 2020