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Protection of Storage Under Sloped Ceilings – Phase 2 – Full Scale Test Matrix

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 are 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.

The Fire Protection Research Foundation initiated this project to undertake modeling analysis in order to understand the potential protection challenges related to sloped ceilings, and to determine the range of scenarios that should be studied further through testing in order to help inform requirements and guidance related to sloped ceilings over storage in NFPA 13, *Standard for the Installation of Sprinkler Systems*. The objective of this research was to build on the computer simulations completed in [Phase 1](#) with additional variables to develop a full scale test plan for future work, which is documented in this report.

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Test Matrix for Protection of Storage Under Sloped Ceilings

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EXECUTIVE SUMMARY

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) “Protection of Storage Under Sloped Ceilings” project seeks to address knowledge gaps related to the impact of sloped ceilings on storage protection. There is currently a lack of clear guidance on how to design fire sprinkler systems for storage protection under these conditions. The overall goal of the project is to develop the technical basis for new sprinkler protection guidance.

The findings from Phase I and II of the project were reviewed to support the development of a test plan for large-scale fire suppression tests. Phase I studied the relevant parameters associated with storage protection under sloped ceilings through an industry survey and numerical simulations of sprinkler activation and water spray patterns. The storage protection survey collected information from over 100 respondents. The survey found the range of ceiling slopes reported by respondents was relatively uniformly distributed from less than 9.5° (slope of 2 / 12) to beyond 26.6° (6 / 12), with most using a full slope configuration. Class I-IV commodities and Group A Plastics are the most common stored commodities, typically in a rack storage configuration. The vast majority of the survey respondents report relying solely on overhead fire sprinklers, with Control Mode Density/Area (CMDA) sprinklers being the most common, followed by Early Suppression Fast Response (ESFR) type sprinklers. The majority of survey respondents report sprinkler deflectors in the parallel-to-ceiling orientation, with the parallel-to-floor orientation being increasingly common as the ceiling inclination is increased.

The Phase I numerical simulations found that sprinkler activation times and patterns for quick-response, ordinary temperature (QR/OT) sprinklers for unobstructed ceilings $\leq 18.4^\circ$ (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 $\geq 26.6^\circ$, and also when standard-response, high-temperature (SR/HT) sprinklers were considered. Spray simulations using pendent K200 lpm/bar^{0.5} (K14 gpm/psi^{0.5}) sprinklers 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 extended the work done in Phase I by considering obstructed ceiling construction, ridges, and additional sprinkler types. The average activation times of QR/OT sprinklers with a ceiling inclination of 9.5° and purlin depths of 0.3 m (12 in.), and a ceiling inclination of 18.4° and purlin depths of 0.1 m (4 in.), were similar to those for horizontal ceilings for the same purlin depths. The presence of a ridge in sloped ceilings marginally affects 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 is placed 6.1 m (20 ft) from the ceiling midpoint. Early activations were not observed when the ridge was placed 12.2 m (40 ft) from the midpoint. Spray simulations with upright K160 lpm/bar^{0.5} (K11.2 gpm/psi^{0.5}) and pendent K240 lpm/bar^{0.5} (K16.8 gpm/psi^{0.5}) sprinklers demonstrated that the parallel-to-floor sprinkler orientation was preferable.

Analysis of the results from Phase I and II guided the development of the large-scale fire suppression tests. The proposed configuration includes an 18 m x 18 m (60 ft x 60 ft) ceiling at inclination angles up to 18.4° (slope of 4 / 12). Obstructed ceiling construction in the form of purlins and girders will be considered with purlin depths up to 0.46 m (18 in.). The proposed fire

source for the tests is a 2 x 6 x 4-tier high rack storage array of FM Global Cartoned Unexpanded Plastic (CUP) commodity with a ceiling clearance of 3.05 m (10 ft). The CUP commodity is consistent with the most common stored commodities identified in the Phase I survey. The size of the rack storage array will be increased from that simulated in Phase I and II (2 x 2 x 3-tier) to allow lateral flame spread within the array which in turn provides a challenging fire suppression scenario. Pendent, K240 lpm/bar^{0.5} (K16.8 gpm/psi^{0.5}) ESFR type sprinklers with an activation temperature of 74 °C (165 °F) will be spaced in a 3.05 m x 3.05 m (10 ft x 10 ft) array on the ceiling. The K240 sprinkler was selected as it was found to be commonly installed in storage applications throughout North America. The parallel-to-floor sprinkler deflector orientation will be used in the majority of tests, as this orientation was demonstrated to be preferable in the Phase I and II simulations. A limited number of tests will also be conducted with the sprinkler deflector orientated parallel-to-ceiling.

The proposed test matrix includes baseline suppression performance tests under an unobstructed, horizontal ceiling, followed by a series of tests with obstructed ceiling construction of various purlin depths with ceiling inclinations up to 18.4° (slope of 4 / 12). Note that the baseline tests will be conducted separately, and will not affect the total number of sloped ceiling tests. Prior to the sloped ceiling tests, FM Global will provide information on acceptable purlin depths for horizontal, obstructed ceilings. A sequence of sloped ceiling tests is proposed with the aim of conducting the minimum number of tests necessary to derive protection recommendations. Resources permitting, a range of supplementary tests are proposed to address additional test configurations such as the use of standard-response sprinklers and the effects of increasing the ceiling clearance above the commodity. Acceptable fire suppression performance will be based on the total number of sprinklers activated, the extent of fire spread, and ceiling steel temperatures compared to the baseline test results.

The test configuration and test matrix proposed in this report provide a means to validate the work done in Phases I and II of this project, and to further develop guidance on storage protection under sloped ceilings through a series of large-scale fire suppression tests.

1.0 INTRODUCTION

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) “Protection of Storage Under Sloped Ceilings” project seeks to address knowledge gaps related to the impact of sloped ceilings on storage protection. There is currently a lack of clear guidance on how to design fire sprinkler systems under these conditions [1-5]. Large-scale suppression tests with sloped ceilings are not readily available [6], and only a few small- and intermediate-scale suppression studies have been conducted [7,8]. The empirical evidence needed to develop suppression system design guidance does not exist.

Phase I [9, 10] of this project included 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 [11, 12]. The Phase I numerical modeling [10] investigated sprinkler activation and sprinkler spray patterns resulting from a fire in a 3-tier high rack storage array of cartoned unexpanded plastic (CUP) commodity under ceilings of various slopes, ranging from a horizontal ceiling to a ceiling with a slope of 33.7° (slope of 8 / 12). Ceiling clearances (between the top of the storage and the ceiling) of 3.05 m and 6.1 m (10 ft and 20 ft) were examined. In the sprinkler spray portion of the numerical modeling, the spray from a pendent, $K200 \text{ lpm/bar}^{0.5}$ ($K14 \text{ gpm/psi}^{0.5}$) sprinkler at 3.5 bar (50 psi) was studied, with the deflector in both the parallel-to-ceiling and parallel-to-floor orientations.

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 [13] evaluated sprinkler activation times and patterns from large-scale growing fires involving a 3-tier high rack storage commodity in the presence of obstructed ceiling construction, ridges and over a range of ceiling inclinations up to 18.4° (slope of 4 / 12). Simulations were also used to study the water-flux distributions and the effect of deflector orientation on additional sprinklers not considered in Phase I, including upright and pendent sprinklers.

This report summarizes the work completed to date on this project for developing guidance on storage protection under sloped ceilings, and proposes a series of large-scale tests to finalize the design guidance.

2.0 PROJECT HISTORY

The Protection of Storage Under Sloped Ceilings project is coordinated by the Fire Protection Research Foundation (FPRF), the research affiliate of the National Fire Protection Association (NFPA). The overall goal of the project is to determine the impact of sloped ceilings on protection of storage and develop the technical basis for new sprinkler requirements and guidance. Phase I of the project developed a research plan for later work, and consisted of a storage protection configuration survey conducted by Custom Spray Solutions (CSS) and numerical simulations under a range of sloped ceiling configurations conducted by FM Global. Phase II considered additional sloped ceiling configurations and sprinklers, with the goal of developing recommendations for large-scale tests. Findings from the work conducted to date are summarized in this section.

2.1 Phase I

Phase I of the Protection of Storage Under Sloped Ceilings project included both a storage protection configuration survey and numerical simulations. The industry survey of storage configurations provided insight into the relevant parameters to consider in future work. Numerical simulations conducted in Phase I examined an unbounded sloped ceiling configuration to gain insight into the sprinkler activation patterns and water-flux distributions. These focused studies helped to identify and prioritize critical issues and knowledge gaps requiring further study.

2.1.1 Storage Protection Configuration Survey

The storage protection configuration survey [1] collected information from over 100 respondents describing the warehouse and storage configurations, and the protection strategy to better understand sloped ceiling protection design challenges. Respondents to the survey included insurers, owners, Authorities Having Jurisdiction (AHJs), designers and contractors. The results of the survey are summarized below:

- A full-slope ceiling was reported by 63% of survey respondents;
- The range of ceiling slopes reported was relatively uniformly distributed from less than 9.5° (slope of 2 / 12) to beyond 26.6° (slope of 6 / 12);
- 43% of survey respondents reported ceiling inclinations less than or equal to 18.4° (slope of 4 / 12);
- Class I-IV commodities and Group A Plastics are the most common stored commodities according to the survey;
- Rack storage of commodities was the most common configuration (73% of respondents);
- The mean overall ceiling clearance and ceiling height reported by survey respondents were 3.05 m (10 ft) and 6.7 m (22 ft), respectively. The variation in the reported values was large;
- 85% of those surveyed rely solely on overhead fire sprinklers;

- Control Mode Density/Area (CMDA) sprinklers were reported by 60% of survey respondents, while Early Suppression Fast Response (ESFR) type sprinklers were reported by 32% of respondents;
- The majority of survey responses reported sprinklers being oriented parallel-to-ceiling; and
- With increasing ceiling slope, survey respondents reported increasing use of sprinklers oriented parallel-to-floor.

2.1.2 Numerical Simulations

FM Global conducted numerical simulations using the computational fluid dynamics (CFD) code FireFOAM [11, 12] to understand the protection challenges associated with sloped ceilings [10]. As part of this study, the ability of FireFOAM to simulate flows below ceilings of various inclinations was validated using existing experimental data. Numerical simulations were then used to evaluate sprinkler activation times and patterns under ceilings with a range of slopes, with large-scale growing fires as plume sources. Spray simulations were also conducted to examine the water mass flux distributions over a rack-storage commodity under sloped ceilings.

The Phase I numerical simulations [10] considered unobstructed ceilings of various inclinations, and made the following conclusions:

- Activation times and patterns for quick-response, ordinary temperature (QR/OT) sprinklers for ceilings $\leq 18.4^\circ$ inclination are similar to those for a horizontal ceiling for the four sprinklers immediately adjacent to the fire source.
- Increasing the ceiling inclination to 26.6° produces significant delays in sprinkler activations on the lower side of the ceiling, and the sprinkler activation pattern is significantly skewed to the elevated side of the ceiling.
- The relatively greater activation delays associated with standard-response, high-temperature (SR/HT) sprinklers may have an adverse impact on protection design.
- Spray simulations with a single ESFR pendent sprinkler directly above the ignition location showed that the sprinkler deflector orientation, parallel-to-ceiling or parallel-to-floor, strongly affects the water flux that reaches the fire source and the pre-wetting area. The parallel-to-floor deflector orientation maintained a consistent water-flux distribution to the fire region irrespective of the ceiling inclination.
- Spray simulations with a fire plume located between four ESFR sprinklers showed that a ceiling inclination of 33.7° adversely affects the overall spray density, regardless of sprinkler deflector orientation, due to the highly-skewed activation pattern at this ceiling slope.
- The parallel-to-floor sprinkler orientation was preferable for the cases studied in Phase I.

2.2 Phase II

Phase II of the Protection of Storage Under Sloped Ceilings project included laboratory testing and numerical modeling to further investigate the effects of sloped ceilings on sprinkler performance for storage protection. The laboratory portion of the study conducted by Custom Spray Solutions (CSS) and Fire & Risk Alliance (FRA) characterized the spray patterns of the sprinklers through detailed near-field spray measurements and examined impingement of the sprays on sloped ceilings at various standoff distances. The spray characterizations and other laboratory testing will be documented in a forthcoming report by CSS.

The Phase II numerical simulations [13] were conducted jointly by FM Global and FRA using the CFD code FireFOAM [11, 12]. These simulations expanded on the work done in Phase I [10] by examining the impact of obstructed ceiling construction (e.g. purlins and girders), ridges, and additional sprinkler types not considered in Phase I. Using a similar approach to that of Phase I, numerical simulations were used to evaluate sprinkler activation times and patterns under ceilings with a range of ceiling slopes, obstructed construction, and ridges, with large-scale growing fires as plume sources. Spray simulations were also conducted to examine the water mass flux distributions over a rack-storage commodity under sloped ceilings with additional sprinkler types not considered in Phase I.

The following conclusions resulted from the Phase II simulations:

- For horizontal ceilings (0°) and purlin depths of up to 0.6 m (24 in.), a marginal increase in the average activation time of QR/OT sprinklers was observed.
- For a ceiling inclination of 9.5° and purlin depths of up to 0.3 m (12 in.), the average activation times of QR/OT sprinklers were similar to those for horizontal ceilings for the same purlin depths. The average activation times were also comparable to the 9.5° unobstructed ceiling.
- For a ceiling inclination of 18.4° and purlin depths of up to 0.1 m (4 in.), the average activation times of QR/OT sprinklers compares favorably with the unobstructed ceiling results. Considerable delays in sprinkler activation were observed on the non-elevated side of the ceiling for purlin depths of 0.2 m (8 in.) and larger.
- The presence of a ridge in sloped ceilings marginally affects the activation times of the four QR/OT sprinklers surrounding the ignition location. Activations near the ridge occur slightly earlier on the near side of the ridge when the ridge is located 6.1 m (20 ft) from the ceiling midpoint. When that ridge is located 12.2 m (40 ft) the effect of the ridge on sprinkler activations are marginal.
- For inclination angles $\geq 9.5^\circ$ with a purlin depth of 0.3 m (12 in.), highly skewed activation patterns are observed for SR/HT sprinklers between the elevated and non-elevated sides that will reduce suppression effectiveness.
- For an inclined ceiling at 18.4° with the ridge located 6.1 m (20 ft) from the CUP array, SR/HT activation times near the ignition region are similar to when the ridge is not present. However, significantly more SR/HT sprinklers activate near the ridge compared to when the ridge is not present. The effect of a ceiling ridge on sprinkler activation patterns appears more significant for SR/HT sprinklers than for QR/OT sprinklers.

- For a single sprinkler above the ignition location when the fire plume is not present, for both the upright K160 lpm/bar^{0.5} (K11.2 gpm/psi^{0.5}) and pendent K240 lpm/bar^{0.5} (K16.8 gpm/psi^{0.5}) sprinklers, increasing the ceiling inclination from 0° to 18.4° caused a slight decrease in the water flux to the top of the rack-storage array, and the deflector orientation had negligible effect on the water-flux distribution.
- For one upright K160 sprinkler directly above a 600-kW fire, the water-flux distribution reduces significantly above the ignition location when the deflector is held parallel-to-ceiling. The same observation also holds true for the pendent K240 sprinkler.
- For ignition among four sprinklers, in the presence of a 2.6-MW fire plume, the performance of the upright K160 sprinkler remained similar, irrespective of the deflector orientation. For the pendent K240 sprinkler, a small decrease in mass flow rate was observed with the parallel-to-ceiling deflector orientation.
- The parallel-to-floor sprinkler orientation was preferable for the cases studied in Phase II.

3.0 RECOMMENDATIONS FOR LARGE-SCALE TESTING

The findings from Phase I and II [9, 10, 13] serve as the basis to establish a full-scale test matrix for Phase III fire testing that will provide sprinkler design guidance for protection of sloped ceilings in storage occupancies. Full-scale tests will be used to confirm and extend the numerical simulations conducted in Phase I and II to examine the fire suppression performance for storage protection under sloped ceilings. This section presents the configuration and rationale for a series of large-scale fire suppression tests.

3.1 Approach

Large-scale fire suppression tests for storage protection require significant time and effort to complete. As a result, it is not practical to consider the full breadth of parameters using large-scale testing. Work done in Phase I and II established the range of conditions to consider via an industry survey, and worked to reduce the parameter space using analysis of numerical simulations. The analysis conducted so far in this project will be used to inform the parameters in the large-scale testing. In general, the recommended configuration was selected to provide challenging fire suppression scenarios for the large-scale tests.

The focus of Phase III is on variables that may affect suppression performance. The approach presented does not include an exact list of all tests that will be performed. Rather, conditions for subsequent tests will depend on the results of those conducted earlier. This approach allows the broadest range of conditions to be examined while minimizing time and effort.

3.2 Test Configuration

The configuration outlined below is intended to provide guidance based on realistic conditions, while remaining consistent with the configuration used in the numerical simulations. Details on the recommended configuration for the large-scale fire tests are provided below, including the ceiling configuration, a description of the fire source, sprinkler details, and instrumentation.

3.2.1 Ceiling Configuration

The analysis conducted in Phase I and II showed the potential for reduced suppression performance at ceiling inclinations greater than 18.4°. Ceiling inclinations of 0°, 9.5°, and 18.4° will be considered. The horizontal (0°) ceiling will be used to establish baseline suppression performance using the same fire source, sprinkler configuration, and instrumentation used in the subsequent sloped ceiling tests. Table 1 summarizes the ceiling configuration parameters.

The ceiling will have dimensions of 18 m x 18 m (60 ft x 60 ft), and be constructed of noncombustible materials. The numerical simulations used a 24 m x 24 m (80 ft x 80 ft) ceiling, however a sloped ceiling of this size is not practical given the limits of existing large-scale testing facilities and the effort required for construction. The recommended ceiling dimensions are large enough to provide realistic fire suppression performance data within the limits of existing testing facilities.

The ceiling clearance (i.e., the distance between the top of the rack storage commodity and the ceiling) will be 3.05 m (10 ft). This distance is consistent with values found in the Phase I industry survey, and with the numerical simulations in Phase I and II. By increasing the ceiling clearance to 6.1 m (20 ft), the modeling results in Phase I and II showed minor increases in the average activation time of the four QR/OT sprinklers surrounding the ignition location.

Ceiling obstructions consisting of sheet metal strips of various depths will be used to examine fire suppression performance for obstructed ceiling construction. The numerical simulations used simplified obstruction geometry for the girders and purlins rather than C- and Z-shaped purlins or other common structural steel shapes. This simplified geometry is sufficient to mimic the flow obstruction provided by the actual structural elements. Purlin depths of 0.15 – 0.46 m (6 – 18 in.) will be used, with a purlin spacing of 1.5 m (5 ft). Girders will be located below the purlins, and will have a depth of 0.6 m (24 in.) and a spacing of 7.6 m (25 ft). Results from the Phase I and II numerical simulations will be used to determine the purlin depths for the initial tests. Purlin depths considered in subsequent tests will be based on the suppression performance observed in the previous tests. The evaluation criteria used to determine successful suppression performance are outlined in Section 3.4. Purlin depths will be increased if acceptable fire suppression performance is demonstrated, or decreased if unacceptable suppression performance is observed. If acceptable fire suppression performance is not demonstrated with obstructed ceiling construction, tests will be conducted with inclined unobstructed ceilings.

Table 1. Ceiling configuration parameters.

Ceiling clearances (h)		3.05 m (10 ft)	
Ceiling	inclinations (θ)	9.5°	18.4°
	slopes	0.167 2 / 12	0.333 4 / 12
Purlin	depths (d_p)	0.15 - 0.46 m (6 - 18 in.)	
	separation distance (w_p)	1.5 m (5 ft)	
Girder	depth (d_g)	0.6 m (24 in.)	
	separation distance (w_g)	7.6 m (25 ft)	

Ceiling ridges will not be considered as one of the parameters for the large-scale tests. The ridge simulations conducted in Phase II showed relatively minor changes in the sprinkler activation times of the four sprinklers surrounding the ignition location when a ridge was present. The increased number of sprinkler activations, and decrease in sprinkler activation times near the ridge, indicate the ridge may pose more of a water demand issue than directly affecting fire suppression performance. Another major consideration is the increased difficulty in constructing a structure with a ridge.

3.2.2 Fire Source

The fire source used in the numerical simulations in Phase I and II consisted of a growing fire on a 2 x 2 x 3-tier high rack storage array of FM Global Cartoned Unexpanded Plastic (CUP) commodity, with a maximum convective heat release rate (HRR) of 15 MW. The recommended fire source for the large-scale tests is a 2 x 6 x 4-tier high rack storage array of CUP commodity. Use of the CUP commodity is consistent with the results of the Phase I survey that found Class I-IV commodities and Group A Plastics are the most common stored commodities. The height and width of the rack storage array will be expanded from the commodity used in the numerical simulations to allow lateral flame spread to occur so as to provide a realistic and challenging fire suppression scenario. Figure 1 and Figure 2 show plan and elevation views, respectively, of the

recommended rack storage array. Single row target arrays of CUP commodity will also be located on each side of the main array, separated by a 1.2 m (4 ft) aisle. The main array and target arrays will be aligned with the purlins on the ceiling (i.e., perpendicular to the ceiling slope). This arrangement is typical in industry to maximize usable storage space.

As shown in Figure 1 and Figure 2, the rack storage array will be offset towards the non-elevated side of the ceiling. The center of the rack storage array will be 5.3 m (17.5 ft) from the non-elevated end of the ceiling. This offset allows for approximately 70% of the ceiling area to be located on the elevated side of the ceiling, while still maintaining two rows of sprinklers on the non-elevated side. The Phase I and II simulations demonstrated skewed sprinkler activation patterns for sloped ceilings, with fewer sprinkler activations occurring on the non-elevated side. Offsetting the rack storage array under the ceiling allows the ceiling area to be maximized.

The rack storage array will be ignited with a flaming ignition source near the bottom of the central transverse flue, 0.6 m (2 ft) from the center of the array, as shown in Figure 1. The ignition source for the CUP commodity will be relatively small, such as the FM Global standard igniter, and the fires will be allowed to develop naturally. Details of the setup will be finalized during the Phase III planning stage.

The selection of the ignition location between four sprinklers was made, in part, for consistency with the conclusions from Phases 1 and 2. This work showed biased sprinkler activations toward the elevated side of the ceiling, likely affecting protection performance, when ignition occurs among four sprinklers. Similar results were also observed in sloped ceiling testing conducted at UL [14] that examined ignition locations among four and between two sprinklers. Although multiple test variables changed between tests, the test conducted with the ignition located among four sprinklers resulted in the highest ceiling temperatures and the greatest number of standard-response sprinkler activations of the four tests.

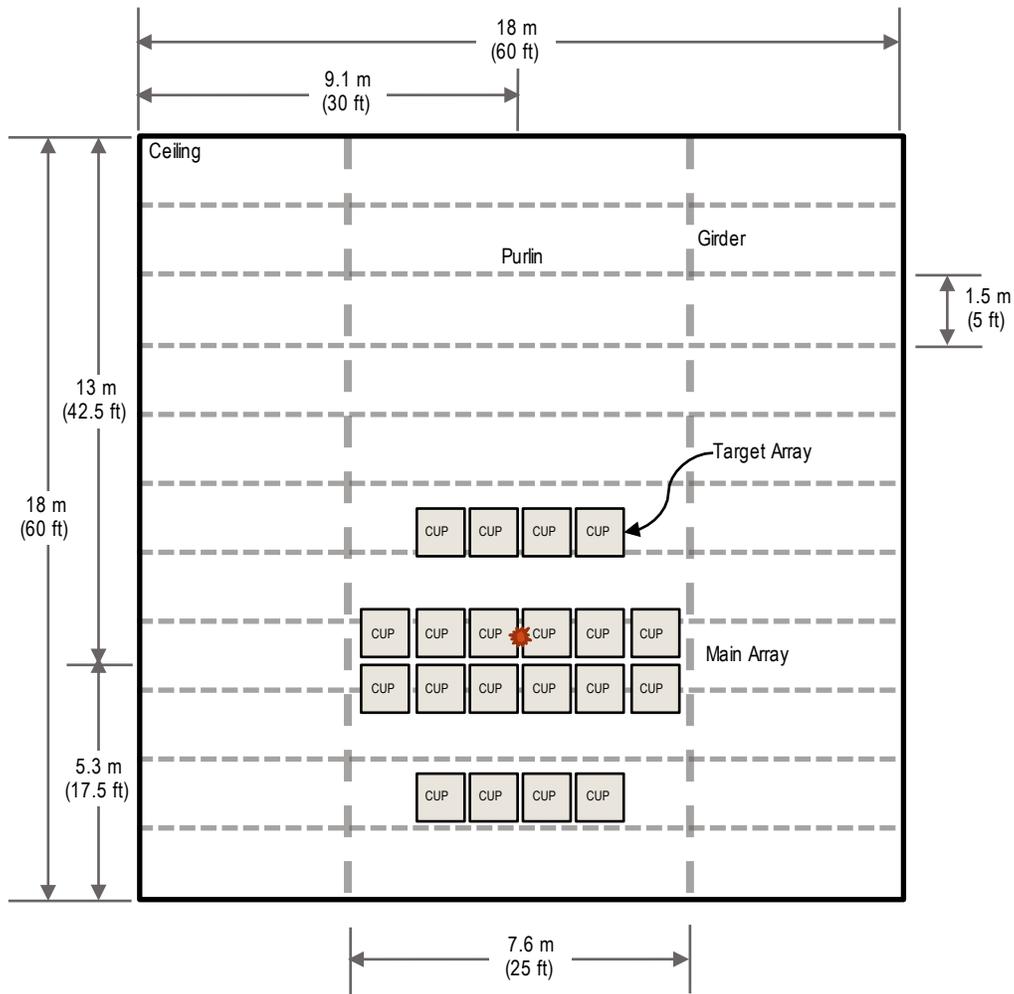


Figure 1. Plan view of rack storage test array.

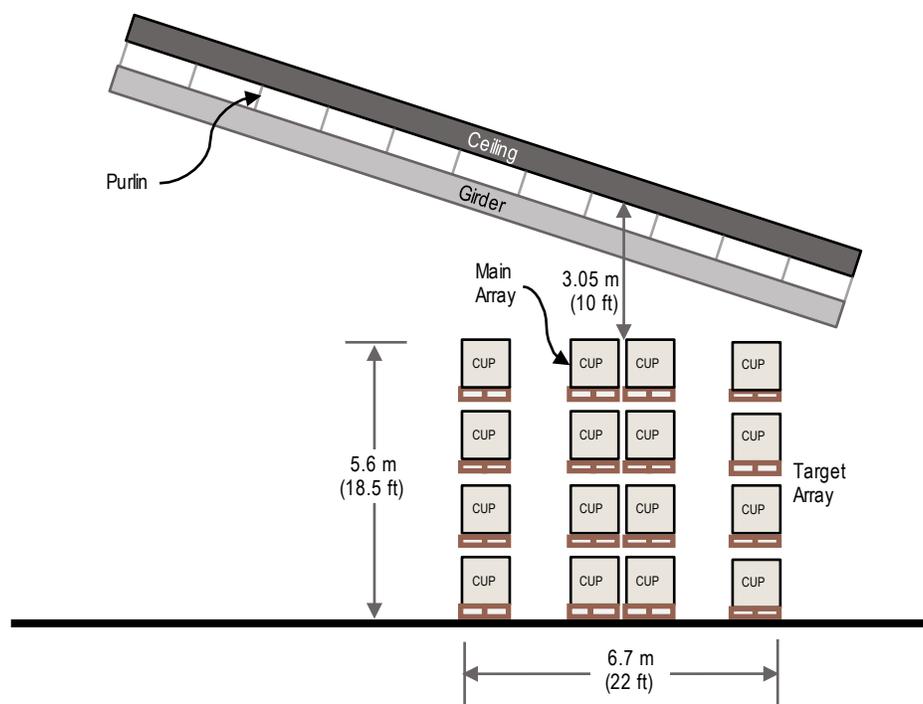


Figure 2. Elevation view of rack storage test array.

3.2.3 Sprinklers

The recommended sprinkler configuration for the large-scale testing will include pendent K240 lpm/bar^{0.5} (K16.8 gpm/psi^{0.5}) ESFR-type sprinklers. ESFR-type sprinklers were selected for the tests for several reasons. ESFR-type sprinklers were used extensively in Phases I and II numerical modeling studies, and consistency with the previous phases of the project will maximize the benefit that can be obtained from the tests. In addition, ESFR-type wet sprinkler systems are predominantly used in the field when ceiling-only protection options are available. CMSA sprinklers were not considered because the Phase I survey indicated that the use of CMSA sprinklers were reported by 6% of respondents. From a testing standpoint, the design area of a CMDA sprinkler system, i.e., number of allowable sprinkler operations, exceeds the size of the proposed test structure.

Sprinklers will be spaced at 3.05 m x 3.05 m (10 ft x 10 ft) intervals. The sprinklers will be offset such that four sprinklers will surround the center of the rack storage array, as shown in Figure 3. Details on the arrangement of sprinkler piping and means of support for the piping will be determined with the testing laboratory during the Phase III planning stage to ensure both upright and pendent sprinkler deflector orientations can be accommodated.

The sprinklers will utilize an ordinary temperature thermal element with an activation temperature of 74 °C (165 °F), with the thermal element located 0.33 m (13 in.) below the ceiling (measured perpendicular to the ceiling). These sprinkler parameters are consistent with the Phase I and II numerical simulations, and the K240 sprinkler is commonly used for storage protection.

When purlins deeper than 0.3 m (12 in.) are considered, there is a concern that obstruction of the sprinkler spray pattern may occur with the sprinkler thermal element located 0.33 m (13 in.) below the ceiling. The Phase 2 simulation results were further analyzed to determine the effects

of lowering the sprinkler thermal element below the 0.33 m (13 in.) distance on sprinkler activation times [15]. This analysis showed that the sprinkler thermal element could be lowered to 0.46 m (18 in.) perpendicular distance below the ceiling for ceilings inclined up to 18.4°, without significantly impacting the sprinkler activation times. This provides a potential means of addressing the spray impingement concerns for deeper purlins. In addition, a series of intermediate-scale cold flow sprinkler tests are planned to occur prior to the full-scale suppression tests that will also address the spray impingement concern.

The pressure and flow rate of the sprinklers will be determined from baseline tests conducted under an unobstructed, horizontal ceiling. The fire source, sprinkler configuration, and instrumentation used in the sloped ceiling tests will be identical to the baseline. A pressure of 2.4 bar (35 psi), which corresponds to a flow rate of 379 Lpm (100 gpm) for the K240 sprinkler, will be used as a starting point for the first baseline test.

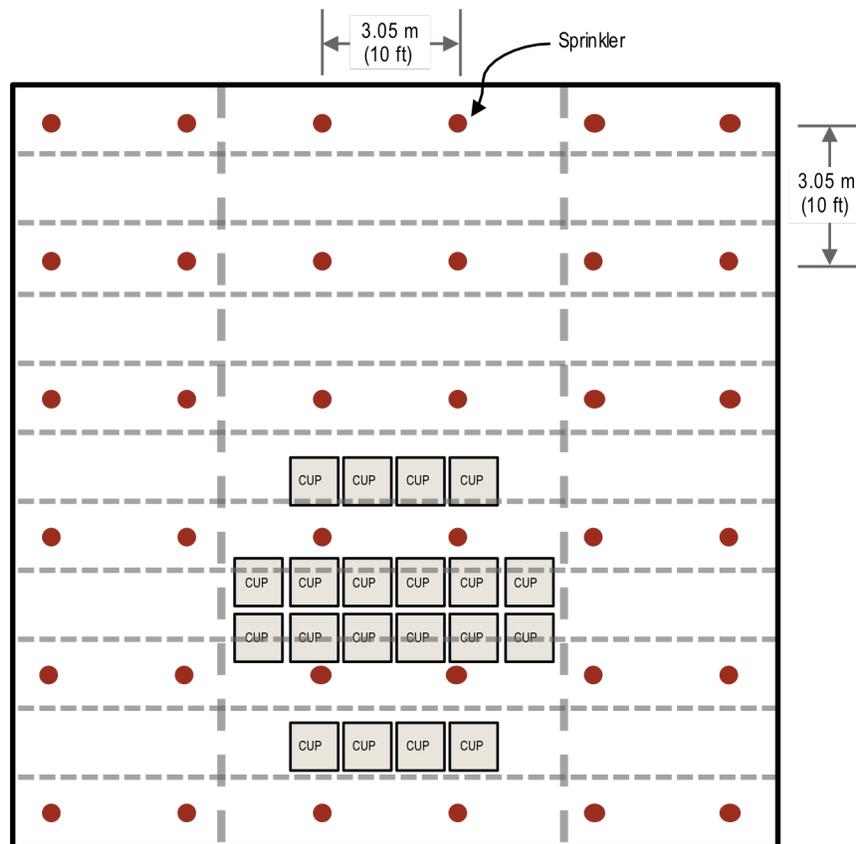


Figure 3. Plan view of sprinkler system layout

3.2.4 Instrumentation

Instrumentation will be included to monitor and document the conditions during the tests. The following instrumentation is recommended:

- Each sprinkler will be electronically monitored to determine its activation time. The pressure and flow rate of the sprinkler system will also be monitored.

- An array of 0.8 mm (20-gage), bare-bead, Type K (chromel-alumel) thermocouples, will be placed 0.15 m (6 in.) below the ceiling to measure gas temperatures. The thermocouples will have an RTI of approximately $8 \text{ (m-s)}^{0.5}$ ($14.5 \text{ (ft-s)}^{0.5}$).
- Simulated Thermal Elements (STEs) will be used to estimate sprinkler activation times at additional locations. The STEs will be located 0.33 m (13 in.) below the ceiling. It is recommended to space the STEs in a 2.4 m x 3.7 m (8 ft x 12 ft) layout on the ceiling to examine an alternative sprinkler layout. The 3.7 m (12 ft) spacing will be along the direction of the purlins.
- Still photography and video will be used to document all tests, from multiple viewpoints.

3.3 Test Matrix

3.3.1 Baseline Evaluation with Horizontal Ceilings

The initial tests conducted in the series will establish baseline sprinkler protection benchmarks using an unobstructed, horizontal ceiling, if existing data is not already available. These baseline tests will not affect the total number of sloped ceiling tests included in the test matrix. Figure 4 is a flowchart that provides guidance on conducting the baseline tests. A pressure of 2.4 bar (35 psi), which corresponds to a flow rate of 379 Lpm (100 gpm) for the K240 sprinkler, will be used for the first baseline test. The fire source, sprinkler configuration, and instrumentation in the sloped ceiling tests will match those used in the baseline test to effectively evaluate the effect of ceiling sloped on the protection performance.

The maximum number of acceptable sprinkler activations will be based on the recommendations in NFPA 13 [1] and FM Global Data Sheet 8-9 [4]. However, the recommendations in these documents include safety factors determined from engineering judgement. For comparison of the sloped ceiling test results, the baseline horizontal ceiling test should not consider the safety factors. Other parameters, such as moisture content in the cartoned commodity that have been shown to significantly affect fire test performance, should also be accounted for while selecting the baseline conditions. Therefore, in case the baseline test has not been conducted previously at the same test facility accounting for conditions like acceptable commodity moisture content levels, it is essential to conduct the test(s) as part of the present testing plan. The intent of developing the baseline conditions, however, is not to establish/develop protection guidance for the standards documents. If acceptable suppression performance is not achieved with a sprinkler operating pressure of 2.4 bar (35 psi), the baseline test will be repeated with an increased pressure until acceptable performance is demonstrated. Conversely, if the fire is suppressed with only a few sprinklers, the baseline test will be repeated with a lower sprinkler pressure. Once an appropriate sprinkler discharge is determined, it will remain constant for the subsequent sloped ceiling tests.

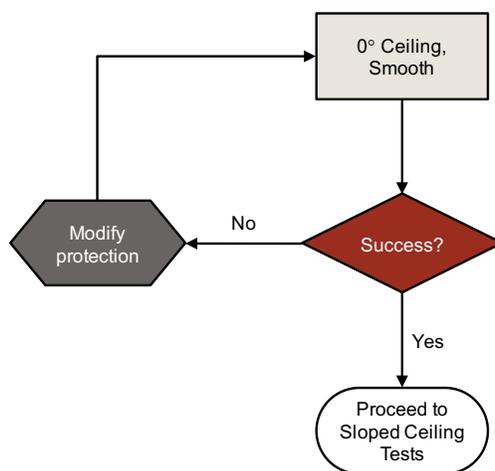


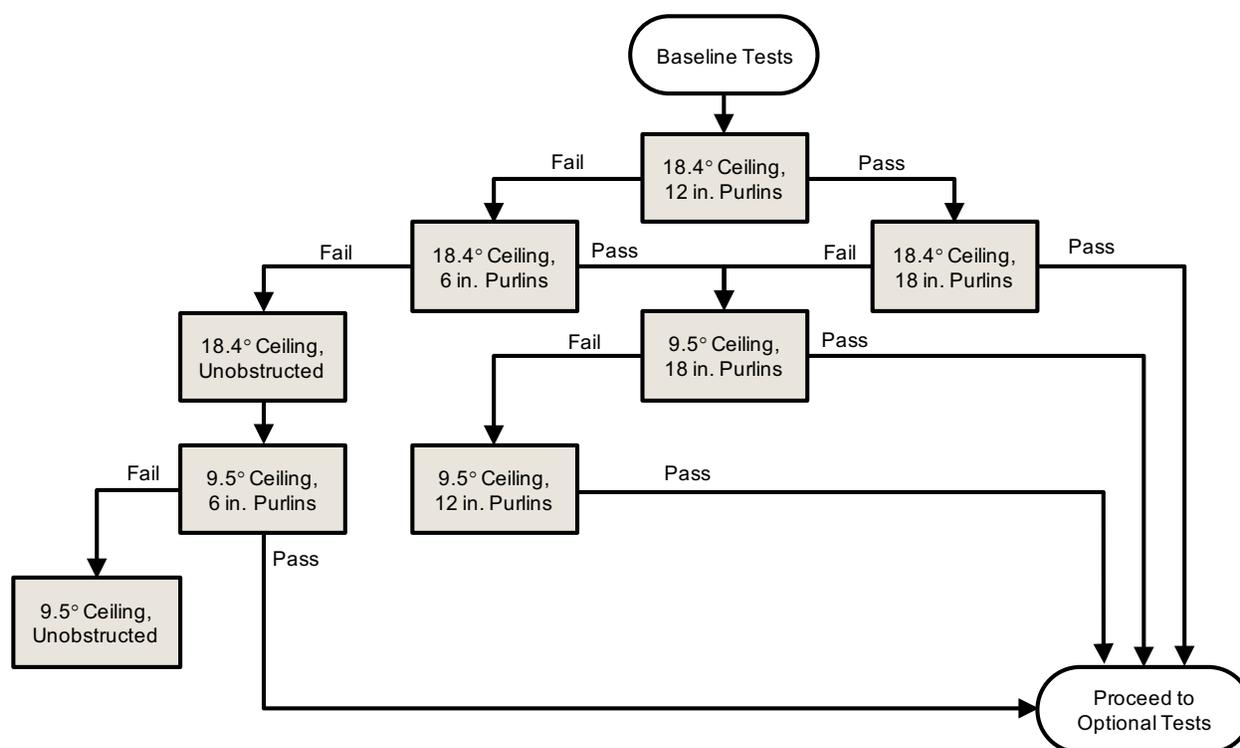
Figure 4. Flowchart for baseline tests.

Once baseline sprinkler protection conditions are established with an unobstructed, horizontal ceiling, FM Global will provide information on acceptable purlin depths for horizontal obstructed ceilings prior to the sloped ceiling tests. If acceptable performance is not demonstrated with deeper purlins for the horizontal ceiling, the sloped ceiling test matrix will be revised accordingly.

3.3.2 Sloped Ceiling Evaluation

Once the baseline testing is completed, the test series will consider fire suppression performance under sloped ceilings. Due to the significant time and effort involved, only a limited number of tests will be conducted. To maximize the benefit obtained from the tests, the proposed test matrix was informed by the numerical simulations conducted in Phase I and II. The numerical simulations showed that as the purlin depth is increased, significant delays in sprinkler activation times are observed. Based on the analysis in Phase II, initial purlin depths examined in the large-scale tests will be 0.3 m (12 in.) for the 18.4° ceiling inclination.

Figure 5 provides guidance on the recommended sequence for the large-scale tests. This flowchart minimizes the required number of tests, while still covering the range of relevant conditions. The first test will involve a ceiling inclination of 18.4° with 0.3 m (12 in.) deep purlins present. The intent of starting with the 18.4° ceiling inclination is that if successful fire suppression performance is demonstrated at the greater ceiling inclination, tests at the lower ceiling inclination with the same purlin depth may be unnecessary. If, instead, unsuccessful suppression performance is observed, the purlin depth will be decreased in the next experiment. This process will be repeated until successful suppression performance is demonstrated. Recommendations will be based on the greatest purlin depth at which successful suppression performance is achieved. If unsuccessful suppression performance is observed with an unobstructed ceiling (i.e. no purlins/girders), no protection recommendations will be made for that ceiling inclination.



Tests will be conducted with the sprinkler deflector in the parallel-to-floor orientation. Once a protection point is established for a given ceiling inclination, the test will be repeated with the parallel-to-ceiling orientation.

Figure 5. Flowchart for sloped ceiling tests.

The industry survey conducted in Phase I found that the parallel-to-ceiling sprinkler deflector orientation is a common practice. However, the numerical simulations in Phase I and II found that there was a decrease in the delivered water flux to the commodity using the parallel-to-ceiling sprinkler deflector orientation as the ceiling inclination increased. Considering both orientations for all test conditions would significantly increase the number of tests. Tests will be conducted with the sprinkler deflectors oriented parallel-to-floor. Once a protection point is established for a given ceiling inclination, the test will be repeated with the sprinkler deflectors in the parallel-to-ceiling orientation.

Pending the results of the tests outlined in Figure 5, if recommendations for protection guidance for sloped ceilings with obstructed construction are established in only a few tests, it is recommended that additional tests be conducted to consider other conditions such as the use of standard-response sprinklers and the effect of increasing the ceiling clearance above the commodity.

An optional configuration to consider is the use of standard-response sprinklers. Standard-response sprinklers are commonly used in storage protection applications. However, the numerical simulations in Phases I and II found greater sprinkler activation delays and skewed activation patterns for standard-response sprinklers. These tests would provide guidance on how to address protection for existing facilities with standard-response sprinklers, and whether standard-response sprinklers should continue to be recommended as a protection strategy for these applications.

Another optional configuration to consider is to increase the ceiling clearance (i.e. the distance between the top of the commodity and the ceiling). The storage protection survey conducted in Phase I found a large amount of variation in the reported ceiling clearances by respondents. Simulations conducted in Phase I and II considered ceiling clearances of 3.05 (10 ft) and 6.1 (20 ft), and showed that sprinkler activations near the ignition location were slightly delayed at the greater ceiling clearance for QR/OT sprinklers. These tests will be used to determine if the activation delays resulting from increased ceiling clearance impact suppression performance. The ceiling clearance will be increased by moving the rack storage array from the offset location shown in Figure 2 towards the center of the ceiling. This approach enables greater ceiling clearances to be examined without significant changes to the structure.

3.4 Evaluation Criteria

The following parameters will be evaluated to establish acceptable fire suppression performance:

- **Number of sprinkler activations** – The maximum number of acceptable sprinkler activations in the tests will be based on the recommendations in NFPA 13 and FM Global Data Sheet 8-9, along with the results of the baseline test with a unobstructed, horizontal ceiling.
- **Extent of fire spread** – Fire spread within the main array shall not reach the extents of the array. Ignition of the target array is permitted, as long as fire spread does not extend to the back of the target array.
- **Ceiling Steel Temperature** – Temperatures of simulated structural steel at the ceiling will not exceed 538 °C (1000 °F).

4.0 CONCLUSIONS

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) Protection of Storage Under Sloped Ceilings project seeks to address knowledge gaps related to the impact of sloped ceilings on storage protection. There is currently a lack of clear guidance on how to design fire sprinkler systems for storage protection under these conditions. The overall goal of the project is to develop the technical basis for new sprinkler requirements and guidance.

The findings from Phase I and II of the project were reviewed, to support the development of a plan for large-scale fire suppression tests. Phase I studied the relevant parameters associated with storage protection under sloped ceilings through an industry survey and numerical simulations of sprinkler activations and water spray patterns over a range of ceiling inclinations. Phase II extended the work done in Phase I by considering obstructed ceiling construction, ridges, and additional sprinkler types.

The proposed large-scale tests will include an 18 m x 18 m (60 ft x 60 ft) ceiling at inclination angles up to 18.4° (slope of 4 / 12), with a ceiling clearance of 3.05 m (10 ft) above the commodity. Obstructed ceiling construction in the form of purlins and girders will be considered with purlin depths up to 0.46 m (18 in.). The proposed fire source for the tests is a 2 x 6 x 4-tier high rack storage array of FM Global Cartonized Unexpanded Plastic (CUP) commodity, with target arrays of CUP commodity on each side of the main array. Pendent, K240 lpm/bar^{0.5} (K16.8 gpm/psi^{0.5}) ESFR-type sprinklers with an activation temperature of 74 °C (165 °F) will be spaced in a 3.05 m x 3.05 m (10 ft x 10 ft) array on the ceiling. The parallel-to-floor sprinkler deflector orientation will be used in the majority of tests, as this orientation was demonstrated to be preferable in the Phase I and II simulations. A limited number of tests will also be conducted with the sprinkler deflector oriented parallel-to-ceiling.

The proposed test matrix includes baseline suppression performance tests under an unobstructed, horizontal ceiling, followed by a series of tests with obstructed ceiling construction of various depths with ceiling inclinations up to 18.4° (slope of 4 / 12). Prior to the sloped ceiling tests, FM Global will provide information on acceptable purlin depths for horizontal, obstructed ceilings. A sequence of sloped ceiling tests is proposed with the aim of conducting the minimum number of tests necessary to derive protection recommendations. Resources permitting, a range of supplementary tests are proposed to address additional configurations such as the use of standard-response sprinklers and the effect of increasing the ceiling clearance above the commodity. Acceptable fire suppression performance will be based on the total number of sprinklers activated, the extent of fire spread, and ceiling steel temperatures compared to the baseline test results.

The tests proposed in this report provide a means to validate the work done in Phases I and II of this project, and to further develop guidance on storage protection under sloped ceilings through a series of large-scale fire suppression tests.

5.0 REFERENCES

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