FIRE PROTECTION AT HIGH CEILING CLEARANCE FACILITIES

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ABSTRACT

The number of the buildings with a high clearance between the floor and the ceiling such as airport terminals, shopping malls, atria, movie studios, theaters, convention halls, and hotel lobbies has been steadily increasing in recent years. These structures pose a unique challenge to fire safety engineers and building code officials alike because of their high clearances between the floor and the ceiling. One of the most practical yet most reliable protection schemes is installing automatic fire sprinklers on the ceiling. Two critical issues regarding the sprinkler operation at high ceiling clearance facilities are: (1) whether the sprinklers installed on such a high ceiling would operate when there is fire, and (2) what are the proper sprinkler parameters that would effectively control fire once the system activates? Utilizing the test data collected through a number of fire tests in a high ceiling clearance facility, this paper will discuss the two issues.

KEYWORDS: High-ceiling clearance, Automatic fire sprinkler, Sprinkler skipping

INTRODUCTION

The population of the buildings with a high clearance between the floor and the ceiling has been steadily increasing in recent years. Some examples of the facilities with a high ceiling clearance that are not built for the purpose of storage are airport terminals, large shopping malls, atrium spaces, movie studios, theaters, sports arenas, and hotel lobbies. They are a familiar feature in everyday life. These structures pose a significant challenge to fire safety engineers and building code officials alike because of their high clearances between the floor and the ceiling. Because in most cases there are not many alternative fire protection schemes available for the buildings with high ceiling clearances beyond sprinkler installation, a frequent concern is whether sprinklers on such high ceilings would operate and be effective. In some cases, the judgment that sprinklers would not operate may lead to a waiver of sprinkler installation and in consequence, facilities could be left without any proper means of automatic fire protection.

One of the most practical yet most reliable protection schemes is installing automatic fire sprinklers on the ceiling. Two critical issues arise in considering in sprinkler operation at high ceiling clearance facilities. The first is whether the sprinklers installed on such a high ceiling would operate when there is fire. The second is identifying the parameters that affect the effectiveness of sprinkler operation against fire. Utilizing test data collected through a number of fire tests in a high ceiling clearance facility [1], this paper will address some aspects of the two issues.

ASSESSING SPRINKLER ACTUATION ON HIGH CEILINGS

An assessment of whether a sprinkler on a high ceiling would activate or not is rather straightforward once the fire history, i.e. heat release rate vs. time, is given. The actuation of the first sprinkler mainly depends on the ceiling clearance from the fire source on the floor, the heat release rate of fire, the temperature rating of the sprinkler, and the response time index (RTI) of the sprinkler. It was also found[2] that the actuation would depend upon whether the fire source is three-dimensional or plane two-dimensional.

Steady plane pan fires are being used frequently in order to assess the fire size that would actuate the first sprinkler on high ceilings because of its convenience. Analyses in Ref. 2 show that the critical fire sizes for the sprinkler actuation determined by the pan fire tests are likely to be substantially different from those in more realistic fire scenarios. Thus, any conclusion as to whether sprinklers on a high ceiling would actuate or not based on pan fire exposure should be properly assessed.

An analysis in Ref. 2 indicates that when the ceiling clearance is 22.2 m, the threshold fire size for actuation of the ceiling sprinklers expected from a 3-dimensional growing fire load, which is the most likely case of an accidental fire, is 8.9 MW, and that from a 2-dimensional plane pan fire is expected to be 11.7 MW, assuming that the temperature rating of the sprinkler is 74 ^{o}C, RTI = 28 $(m.s)^{1/2}$, the ambient temperature is 15 ^{o}C and the convective portion of the heat release rate from the fire is 0.65. When the ceiling clearance is 26.6 m, with the same sprinkler and convective heat release rate coefficient, the analysis also indicates that it is expected to be 11.5 MW by a 3-dimensaional growing fire load to actuate the ceiling sprinklers (with the ambient temperature at 23 ^{o}C); however, it is expected to be 14.5 MW by a 2-dimesional steady pan fire.

While the steady pan fires are basically two dimensional, the growing fires generally involve three dimensional fire sources. The flames in the growing fires spread horizontally as well as vertically. Thus, at the top of the burning commodity the plume from the growing fires already possesses a sizable amount of momentum that the counterpart from the steady pan fires lacks. A comparison of the growing fire cases with the pan fire cases shows that deciding the threshold fire size that would actuate sprinklers on high ceilings based on pan fire tests will be likely to lead to a wrong conclusion because it takes a much larger fire size in pan fires to have a ceiling temperature that is higher than the sprinkler temperature rating, compared with the fire size in growing fires. When the ability of sprinkler actuation is assessed by using a pan fire test, then one can assume that the expected fire size from a growing fire that would actuate the sprinklers would be about 30% smaller than the threshold pan fire size.

It is very important to find out the accurate threshold fire sizes that would open sprinklers on high ceilings based on realistic fire scenarios. Utilizing existing data, Ref. 2 shows how the fire sizes that would actuate ceiling sprinklers at a certain clearance can be properly estimated. Detailed analyses are given in Ref. 2, thus no more analysis will be provided in this paper.

PARAMETERS AFFECTING EFFICACY OF SPRINKLERS ON HIGH CEILINGS

For proper fire protection, it is critical to install a sprinkler system on a high ceiling that not only will actuate with an anticipated fire size but also would be effective in controlling the fire once the system is engaged. The major parameters that would affect the effectiveness of the sprinkler operation are: the heat release rate of fire, the clearance between the top of the fuel load and the sprinkler location on the ceiling, the wetting susceptibility of the fire load, the orifice diameter, temperature rating and the response time index (RTI) of the sprinkler, and the water pressure at sprinkler operation. Results from seven full scale fire tests[1] will be compared in order to address the effects of those parameters on the effectiveness of sprinklers on fire control. Test results[1] strongly indicate that the sprinkler “skipping” is a prevalent and almost unavoidable phenomenon in wet sprinkler operation at high ceiling facilities and it interferes with the effectiveness of sprinkler in a very significant way. Thus, how the parameters mentioned above are related to the sprinkler skipping would be the main subject of the following analysis.

The “skipping” of sprinkler is a phenomenon in a sprinkler operation that sprinkler opening pattern does not coincide with the logical sequence of the opening. When skipping occurs, sprinklers that are farther away from the fire source open before sprinklers that are closer to the fire source do. The skipping is mostly caused by wetting of sprinkler thermal links by small water drops from operating sprinklers that are carried out by the fire plume[3]. A light skipping is a common occurrence in sprinkler operation when multiple opening is involved and generally does not significantly affect the effectiveness of sprinkler operation. However, it is found[1] that sprinkler skipping is quite intense in operations involving high ceiling clearance scenarios and was judged as one of the most significant factors in determining the effectiveness of sprinkler operations.

At high ceiling clearance facilities, actuation of the first sprinkler is delayed because it takes time to build up the plume temperature higher than the sprinkler temperature rating at the ceiling elevation. Thus, the fire intensity is quite higher than that in lower ceiling clearance cases when the first sprinkler opens. The already intense fire plume carries many small water droplets to adjacent sprinklers, and make thermal links of the sprinklers wet, which in turn creates skipping. Therefore, the factors that are likely to enhance the skipping are: high clearance; high heat release rate from the fire source; high temperature rating, small orifice, and high operating pressure of the sprinkler (small drop size). The high clearance, a high HRR, and the high temperature rating and high RTI of the sprinkler increase plume intensity at actuation of the first sprinkler. The small orifice and the high water pressure at the sprinkler operation may not only increase the discharge angle from the orifice, but also tend to generate a greater number of small droplets that can be easily carried out by the plume to the neighboring sprinklers.

The following test data collected through seven full-scale fire tests at high clearance facilities will show different degrees of skipping related to different test parameters mentioned above. Comparisons of test data will indicate why certain test conditions brings more effective sprinkler operations than others and how the severity of the skipping could have contributed to the outcomes.

TEST DESCRIPTION

The seven fire tests were conducted under an 18.3-m high ceiling using 2.26-m high solid pile FM Global Class 2 commodity in Tests 1 and 2, and 1.73-m high solid pile FM Global Standard Plastic commodity in all the other tests. Detailed descriptions of most of the tests were given in Ref. 1. For some facilities such as hotel lobbies or atria that may have a fire load regarded as relatively light, the Class 2 commodity can be a good representation of the fire hazard. For a facility that is exposed to a limited amount of plastic materials, the potential fire load can be represented by the Standard Plastic commodity. Thus, assessing the fire load to the equivalent commodity classification must be the first job of the fire safety engineers who need to design a proper fire protection system for a facility.

The full-scale fire tests were conducted at the old FM Global Test Center, West Glocester, Rhode Island, USA. The tests were designed to address the concerns mentioned above and provide guidelines for protection of non-storage high-ceiling-clearance occupancies. The fire tests were conducted using fuel arrays that were designed to simulate ordinary hazard fire scenarios.

FIRE TEST PARAMETERS

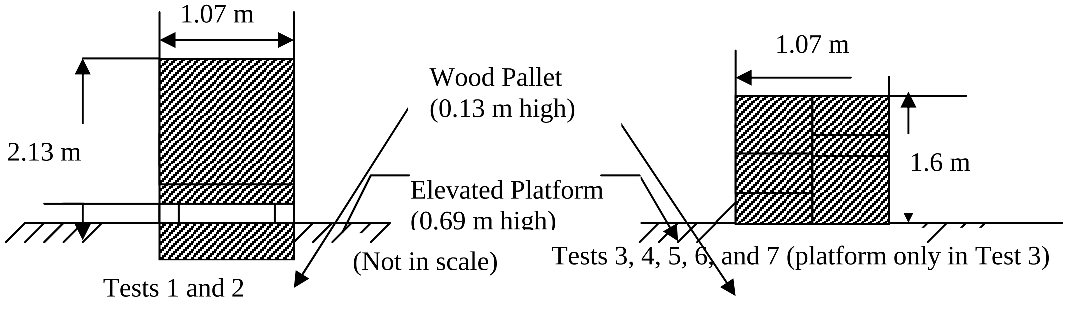


FIGURE 1. Side views of fuel arrays used in the tests

Test Fuels

The FM Global Standard Class 2 Commodity served as the fuel in Tests 1 and 2. The commodity consists of a 1.07 m cube, double, tri-wall corrugated paper carton containing an open bottom sheet metal liner. The cartons have a combined nominal 25 mm thickness. Each fuel stack consisted of two double-up cartons (each 1.07 m x 1.07 m x 1.07 m high) supported on a wood pallet. The FM Global Standard Plastic Commodity served as the fuel in Tests 3, 4, 5, 6 and 7. The Cartoned Unexpanded Group A Plastic Commodity consists of 125 empty polystyrene cups packaged in compartmented, single wall, corrugated paper cartons. Each fuel stack consisted of twelve cartons (each 0.53 m x 0.53 m x 0.53 m high) placed on a wood pallet. (See Fig. 1)

Fuel Array Arrangements

The height of the fuel stacks in Tests 1 and 2 was 2.26 m and that in Tests 3, 4, 5, 6, and 7 was 1.73 m. Since the fuel stacks were placed on a 0.69 m high platform in Tests 1 through 3, the clearance from the top of the fuel arrays to the ceiling was 15.4 m in Tests 1 and 2 and 15.9 m in Test 3; Without the platforms, the clearance was 16.6 m in the other tests. The top view of the fuel array, 64 stacks of commodity arranged 8 by 8, used in Tests 1, 2, 3, and 4 is given in Fig. 2. Stacks were separated by 0.15 m flues. Tests 5, 6, and 7 used a slightly different fuel array configuration. The top view of the three-row array is given in Fig. 3. The fuel stack arrangement simulated a distribution of fire loads in many non-storage occupancies practicing aisle separations. The aisle separation has been commonly adopted as a means of passive fire protection by providing some distances among potential fire loads when the burning of the commodity involved is expected to be relatively intense. Sixteen stacks of the Standard Plastic commodity, arranged 2 by 8, comprised the main fuel array. There were two target arrays, each single six-stack row, 1.5 m apart from the main fuel array. Adjacent stacks were separated by 0.15 m flues.

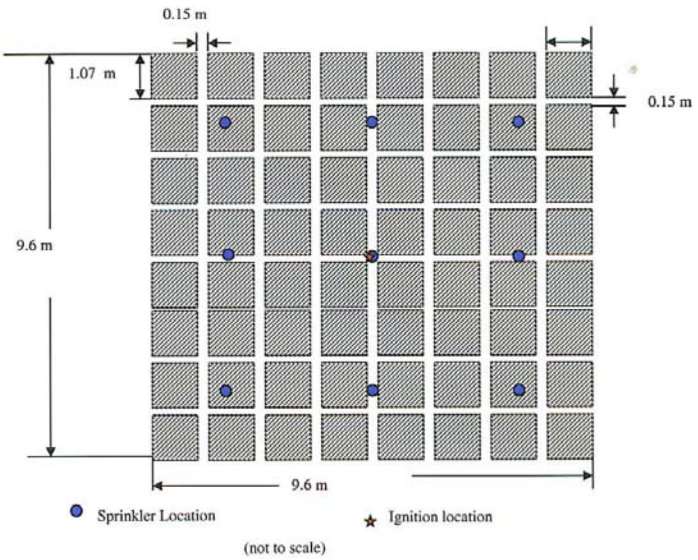


FIGURE 2. Plan view of fuel array used in Tests 1, 2, 3, and 4

Ignition Method

Two igniters, 76-mm diameter x 152-mm long cellucotton rolls, each soaked in 236 ml of gasoline and enclosed in a plastic bag, served as the ignition source. The igniters were located in the center flue of each fuel array along the east-west direction. The ignition location was centered below a single ceiling sprinkler as shown in Figs. 2 and 3. As the test program progressed, ignition directly below one sprinkler was believed to have provided a more conservative fire scenario than other ignition locations do. The ignition directly below one sprinkler tends to produce a more severe skipping than the other ignition locations do. In Test 7, the ignition location was moved below the center of four sprinklers as shown in Fig 4 to see the effect of the ignition location on the skipping.

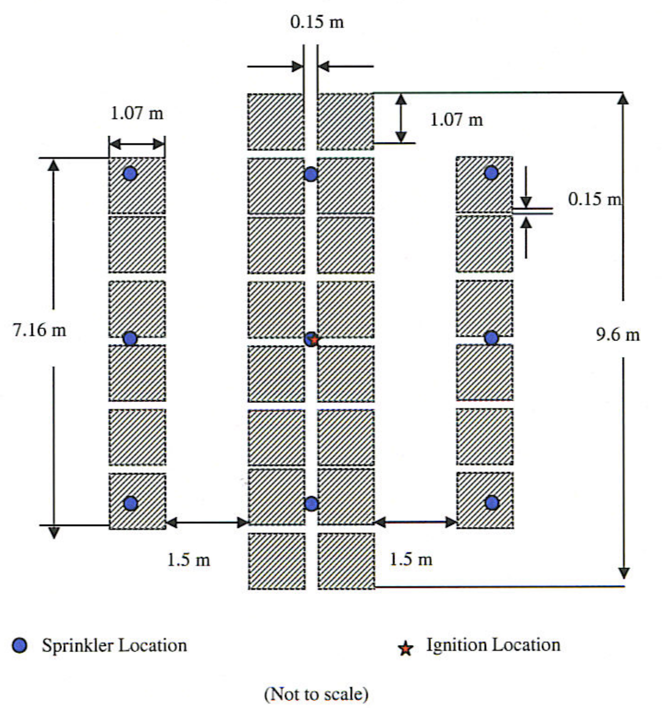


FIGURE 3. Plan view of fuel array used in Tests 5 and 6

Sprinkler Protection

Automatic sprinkler protection in all the tests was provided by upright sprinklers installed just below the ceiling. The temperature rating of the sprinklers used in Tests 1 through 5 was 74 ^{o}C and the Response Time Index (RTI) was 138 (m-s)$^{1/2}$. The temperature rating of the sprinklers used in Test 6 and 7 was 68 ^{o}C and RTI was 28 (m-s)$^{1/2}$.

In Test 1, nominal 12.7 mm orifice sprinklers supplied a 6-mm/min discharge density at a 48 kPa water pressure. In Tests 2, 3, and 5, nominal 13.5 mm orifice sprinklers supplying a 12 mm/min discharge density at a 97 kPa water pressure were used. In Test 4, nominal 13.5 mm orifice sprinklers supplying an 18-mm/min discharge density at a 221-kPa pressure was used. In Tests 6 and 7, nominal 16.3 mm orifice Quick Response, Extra Large Orifice (QR-ELO) sprinklers supplied an 18-mm/min discharge density at 110 kPa. The sprinkler spacing in all the tests was 3 m by 3 m.

TEST RESULTS

The sprinkler opening sequence and the corresponding time of each actuation after ignition are given in Figs. 5 through 8. The dotted boxes represent the areas covered by the fuel array and the red star at the center of fuel array is the location of ignition. The open circles correspond to the un-open sprinklers and the closed circles correspond to the open sprinklers at the end of tests. The numbers next to the open sprinklers correspond to the opening sequence of the sprinklers and the time of each sprinkler opening is provided in the right hand side box.

In Test 1, 17 sprinklers controlled the fire while 15 sprinklers did in Test 2 with a twice more water discharge per each open head. Note that in Tests 1 and 2 the fuel stacks were Class 2 commodity while in all the other tests they were Standard Plastic.

In Tests 3 and 4, the tests were terminated before data provided conclusive results on fire control because of the generation of smoke during the tests exceeded the prearranged test permit. Although there were close to 20 open sprinklers discharging water at the end of the tests, no sign of diminishing fire intensity were detected through the ceiling temperatures measured at 42 locations across the ceiling.

In Tests 5 through 7, the arrangement of the fuel had been changed from the previous densely populated stacks to the main and the target arrays. That increased the area of flame spread when flames jump from the main to the target arrays. Test 5 also was terminated before it provided conclusive results on fire control because the smoke generation exceeded the prearranged test permit. Although there were 26 operating sprinklers at the end of the test, the measured ceiling temperatures indicated no reduction of fire intensity and suggested more opening of sprinklers if the test had continued. In Tests 6 and 7, quick-response extra-large-orifice (QRELO) sprinklers were used and fire was successfully controlled.

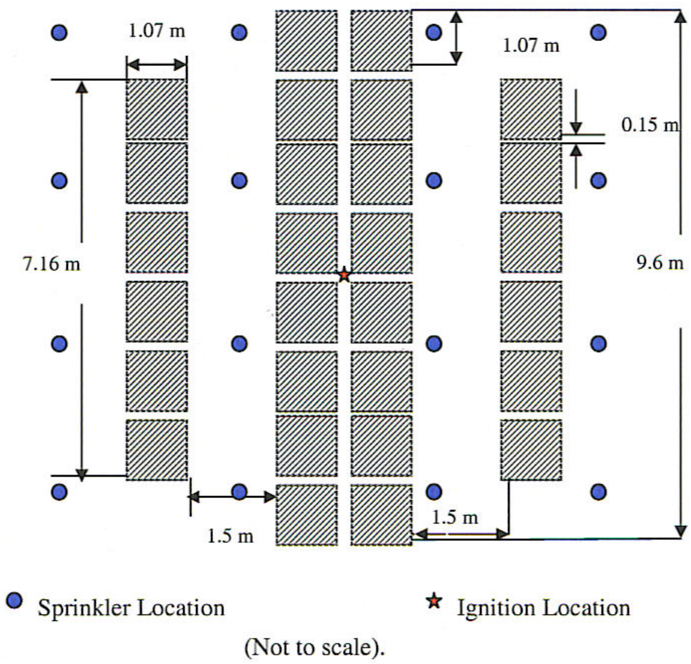


FIGURE 4. Plan view of the fuel arrays used in Test 7

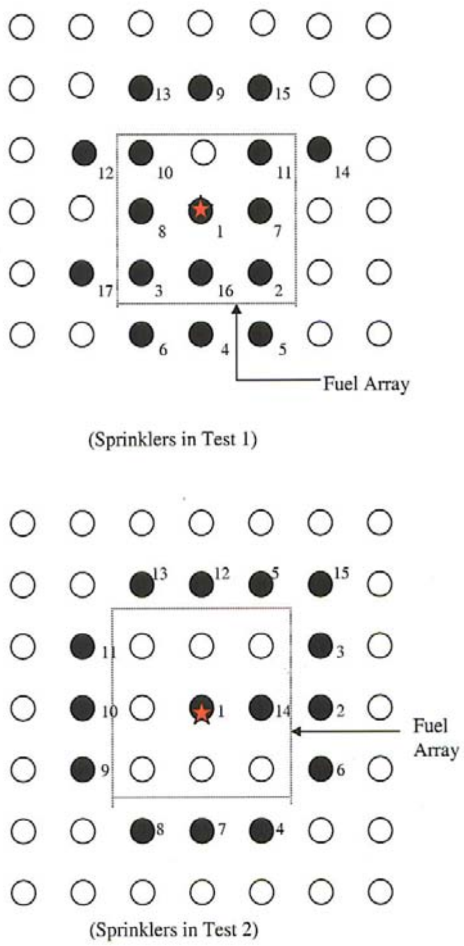
DISCUSSION OF THE TEST RESULTS

The sprinkler skipping, which has not been the dominant parameter in ordinary-clearance facilities in general, was analyzed closely because the test results showed that it played a decisive role in test outcomes. In order to analyze the role of skipping in detail, there was a need to rank the severity of the skipping in each operation so that the degree of contribution could be properly compared. Since there had been no established way of quantifying the severity of the skipping, a way to quantify the severity of skipping had to be devised. An attempt was made based on difference between the idealized sprinkler opening sequence, which would not have any skipping, and a real opening sequence, which would reflect skipping if any. It was hypothesized that quantifying how far a sprinkler opening pattern was deviated from the ideal opening pattern of the corresponding sprinkler operation would be one way of quantifying the severity of the skipping objectively. This quantification is provided as convenience to compare the degree of skipping from one test to another. The more general significance of the parameter is unknown without further research.

The value of the deviation, which would be referred to as “deviation from the ideal opening sequence (**DIOS**)” was computed as follows:

1. In Fig. 9, the ideal sprinkler opening sequence, i.e., from the closest to the farthest from the fire source, with ignition below directly one head is shown. Once the first sprinkler directly above ignition opens, four more sprinklers in the first ring follow. Thus, the opening sequence numbers in the first ring are: 2, 3, 4, and 5, without any preference to any location. The average value of the opening sequence number of the first ring is 3.5. Following the same procedure, the average value per each ring is established as follows: 7.5 at the 2nd, 11.5 at the 3rd, 17.5 at the 4th, 23.5 at the 5th, 27.5 at the 6th, 33.5 at the 7th, 41.5 at the 8th, and 47.5 at the 9th ring.

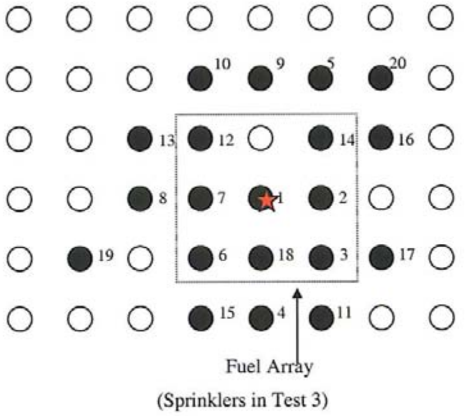
2. In Fig. 10, the ideal sprinkler opening sequence with ignition directly below the center of four heads is shown. The four sprinklers next the ignition location form the first ring. Thus, the opening sequence numbers in the first ring are: 1, 2, 3, and 4, without any preference to any location. The average value of the opening sequence numbers of the first ring is 2.5.



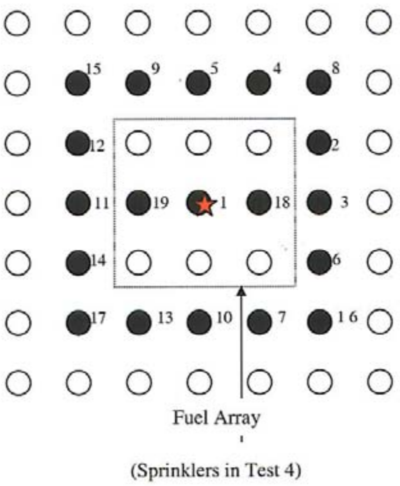
Operating Sequence	Time (min: s)
1	2:28
2	5:21
3	5:29
4	5:34
5	5:49
6	5:58
7	6:01
8	6:12
9	6:13
10	6:20
11	6:26
12	6:29
13	6:38
14	6:47
15	6:48
16	6:58
17	7:20

Operating Sequence	Time (min: s)
1	2:58
2	5:30
3	5:31
4	5:41
5	5:43
6	5:45
7	5:46
8	5:53
9	5:54
10	5:55
11	6:00
12	6:10
13	6:24
14	6:54
15	7:03

FIGURE 5. Comparison of sprinkler opening sequence in Tests 1 and 2



Operating Sequence	Time (min: sec)
1	2:25
2	3:34
3	3:47
4	3:51
5	3:52
6	3:53
7	3:56
8	3:57
9	3:58
10	4:08
11	4:18
12	4:24
13	4:24
14	4:32
15	4:37
16	4:37
17	5:02
18	5:04
19	5:26
20	5:44



Operating Sequence	Time (min: sec)
1	2:12
2	4:01
3	4:04
4	4:06
5	4:06
6	4:11
7	4:19
8	4:25
9	4:26
10	4:28
11	4:30
12	4:30
13	4:32
14	4:34
15	4:49
16	5:00
17	5:03
18	5:16
19	5:49

FIGURE 6. Comparison of sprinkler opening sequence in Test 3 and 4

Following the same procedure, the average value per each ring is established as follows: 8.5 at the 2nd, 14.5 at the 3rd, 20.5 at the 4th, 28.5 at the 5th, and 34.5 at the 6th ring.

1. Take Test 1 in Fig. 5 as an example. Identify the ring number to which each open sprinkler belongs by comparing the rings in Fig. 9. If the real opening sequence number equals to one of the ideal opening sequence numbers belonging to the ring, such as from 2 to 5 at the 1st ring; from 6 to 9 at the 2nd ring; from 10 to 13 at the 3rd ring; from 14 to 21 at the 4th ring; etc., then there is no penalty value. Otherwise, the penalty value will be the absolute value of the real opening sequence number minus the average ideal opening sequence number of the ring mentioned above.

2. Compute the penalty value of each open sprinkler and add them all. The DIOS is the total penalty value divided by the number of the open sprinklers. The higher the DIOS, it was regarded that the more severe the skipping situation is.

In order to see the consistency of the method in determining DIOS, the values of two tests conducted under identical conditions were evaluated. Fig 11 shows sprinkler opening sequences and the opening times of two tests referred to as Tests E1 and E2. The sprinklers used in the tests were upright QRELO (Tr = 68 ^{o}C, RTI = 28 $(m.s)^{1/2}$, P = 317 kPa, 30 mm/min density, 3 m by 3m spacing). The fuel was 4 m high exposed unexpanded plastic and the ceiling clearance was 6 m[4]. Two tests were conducted under the identical operating conditions. In both tests, skipping was severe and 19 sprinklers were opened at the end of the test and fire was controlled. Although the number of the open sprinklers at the end of the test was same, the opening patterns in two tests look quite different. However, when the DIOS was computed following the rules specified above, the values came out very close to each other: 8.0 for Test E1 and 7.8 for Test E2. More data would be necessary to check the consistency further. Being data for large-scale tests under the identical conditions very scarce, however, is the main hindrance on the ongoing efforts in checking the consistency of DIOS in various circumstances. The DIOS of each test obtained by the method above is given in Table 1.

TABLE 1. DIOS of each fire test

Test Number	DIOS	Test Number	DIOS
1	4.7	5	8.6
2	7.6	6	6.4
3	4.8	7	4.3
4	8.0	NA	NA

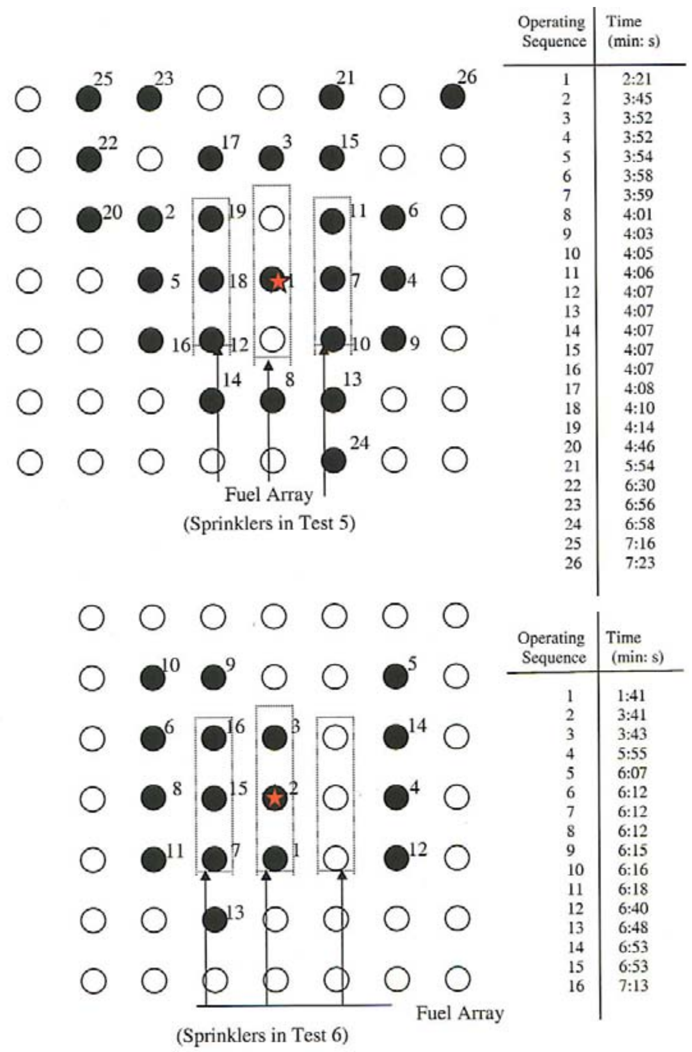
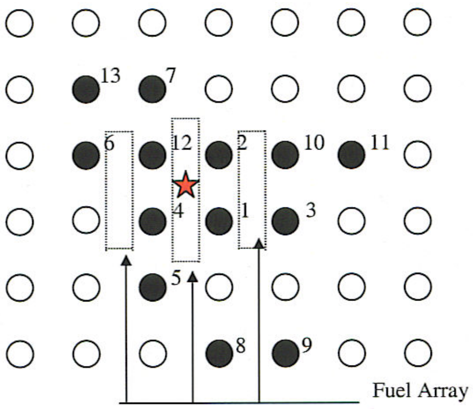


FIGURE 7. Comparison of sprinkler opening sequence in Tests 5 and 6

It is noteworthy to mention that the DIOS at this point is merely intended to reflect the relative ranks in severity of skipping of sprinkler operations under similar circumstances. Thus, its value should not be treated as a universal index in an absolute term in reflecting the severity of skipping. Rather, the value should be accepted as a guideline showing the directions into less severe skipping with varying operating conditions. The DIOS defined above seems to work adequately show the relative ranks of the severity of the skipping in each test.

The performances of sprinkler operations in Tests 1 and 2 were very comparable in terms of the elapsed time before the fire was controlled and the amount of assessed damages. However, the sprinkler operation in Test 2 at the end of the test required as much as 77 % greater total water flow rate than that in Test 1: 2.05 vs. 1.16 m^3/min. The water flow rate per each sprinkler was doubled in Test 2 by increasing the water pressure from 48 kPa in Test 1 to 97 kPa. Since the theoretical volumetric median drop diameter of a sprinkler spray, d_m, varies as $d_m \propto (D^{2/3}\Delta P^{-1/3})^5$, where D is the orifice diameter and ΔP is the water pressure, d_m in Test 2 was about 80 % of that in Test 1 $[(13.5/12.7)^{2/3}\,(97/48)^{-1/3} = 0.82]$, there were many more small droplets compared with those in Test 1, and which, in consequence, increased skipping tendency in the sprinkler operation. The DIOS in Test 2 was 7.6 while that in Test 1 was 4.7. This increase in the severity of the skipping in Test 2 seems to be mainly responsible for the not-much improved performance despite the large increase in the amount of water flow compared with that in Test 1.

In Tests 3 and 4, neither sprinkler operation was successful in controlling fire before the tests were terminated. Although the water spray at each sprinkler in Test 4 was increased by 50 % than that in Test 3, the sprinklers were unable to control the fire. The water pressure was increased from 97 kPa in Test 3 to 221 kPa in Test 4, which reduced the volumetric median drop size by 24 %, which in turn increased the tendency of skipping in Test 4. The DIOS in Test 4 was 8.0 while that in Test 3 was 4.8. One indication is that when the DIOS is high and when the heat release rate of the fuel load is high, just increasing the water flow rate per each open head is unlikely to provide a solution for fire control. The peak convective heat release rate from the center four stacks of the Class 2 commodity in Tests 1 and 2 was close to 5.8 MW and that from the Standard Plastic commodity in Tests 3 and 4 was close to 7.5 MW[2].



Operating Sequence	Time (min: s)
1	1:59
2	1:59
3	3:27
4	3:50
5	3:52
6	3:55
7	3:56
8	3:58
9	4:27
10	4:27
11	4:32
12	4:45
13	4:49

FIGURE 8. Sprinkler opening sequence in Test 7

In Test 5, the sprinkler operational parameters were the same as those in Test 3. However, the DIOS was 8.6, much higher than that in Test 3. The different fuel arrangement in Test 5 expedited fire propagation as flames jumped from the main to the target arrays and in consequence opened more sprinklers that were located farther away from the ignition source and that increased the DIOS. Although there were 26 operating sprinklers discharging 1.75 *l/s* per each head when the test was terminated, there were no sign of dwindling fire intensity. It was determined that the high degree of sprinkler skipping severely damped the effectiveness of sprinkler operation, and was judged that simply increasing the water flow rate per head would not improve the situation.

In Test 6, in order to reduce sprinkler skipping, sprinklers with a larger orifice were sought. Also it was believed that having the quick-response link would reduce the first sprinkler actuation time and that would lessen the severity of skipping too because water can be discharged when the momentum of the plume is not as strong as the one expected with the ordinary-response link.

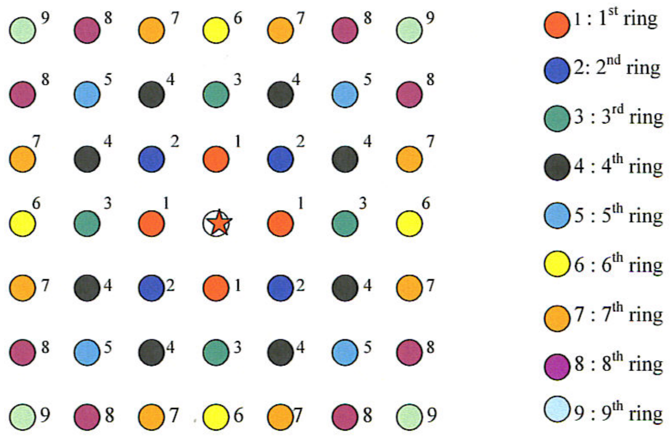


FIGURE 9. Ideal sprinkler opening sequence with ignition directly below one head

Thus, quick-response extra-large-orifice (QRELO) sprinklers were used in Test 6 and they successfully controlled fire. Although the water flow rate per each head was increased by 50 %, the water pressure was increased only by 14 % by having the orifice larger by 20 %, compared with those in Test 5. The theoretical volumetric median drop size actually slightly increased although the water discharge density increased substantially, compared with those in Test 5. The DIOS was 6.1 and 16 sprinklers controlled the fire.

Previous experiences indicated that ignition directly below a sprinkler would promote the skipping tendency because the droplets from the first open head would spread out to the four neighboring heads in the first ring and make them wet. Thus, the ignition directly below one sprinkler would provide a conservative test for systems designed for high-ceiling clearance facilities. That thought was put to a test. Ignition was provided below the center of four sprinklers in Test 7. All the other sprinkler operational parameters were kept the same as those in Test 6. The DIOS was 4.4, an improved value than that in Test 6, which was 6.4. Thirteen sprinklers controlled fire compared with 16 in Test 6.

The current analysis shows how the sprinkler parameters such as temperature rating, orifice size, and operating water pressure can affect the severity of skipping in sprinkler operations at high ceiling clearance facilities. It also shows that just increasing water flow rate per open head, which usually is the first call from fire safety engineers when the sprinkler effectiveness is deemed marginal, may not necessarily bring about desired outcomes. In order to increase water discharge rate per open head with the same sprinkler, the operation pressure has to go up and that increases the severity of skipping under high-ceiling clearance environments. Despite the considerable increase in the discharge density compared with that in Test 3, the higher flow rate did not provide any improved performance in Test 4 due to the increased severity of skipping. The fire was under control only after the skipping situation was alleviated by employing the large-orifice sprinklers in Test 6.

The analysis performed here is based on the test results using the Class 2 and the Standard Plastic commodity as the fire loads. Both materials have good wetting susceptibility, which allowed the fire control be achieved by pre-wetting of the materials. Obviously, the same analysis cannot be generally extended to fires where the wetting susceptibility of the fire sources is in doubt. It also has to be recognized that sprinkler protection systems should be designed on a case by case basis after considering all the parameters involved. The benefit of having the increased water discharge rate per head vs. the deteriorating skipping situation by doing so has to be balanced and a way to reduce the severity of skipping has to be found by employing other options.

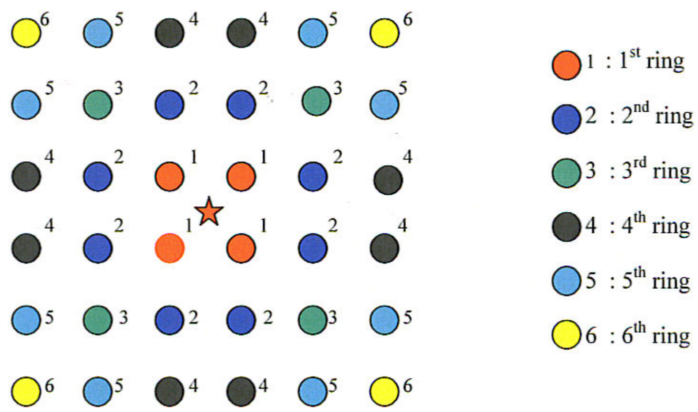
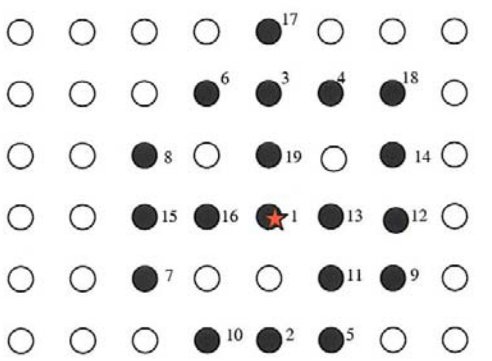


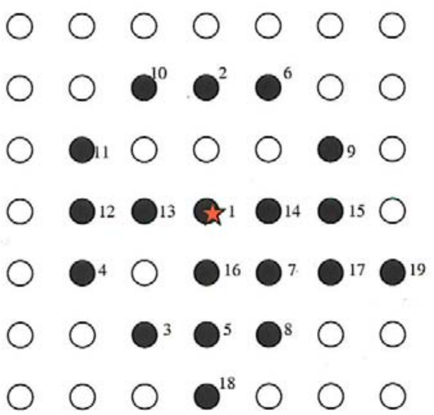
FIGURE 10. Ideal sprinkler opening sequence with ignition below four heads

Sprinkler opening sequence in Tests E1 and E2



Operating Sequence	Time (min: sec)
1	2:48
2	3:22
3	3:29
4	3:34
5	3:38
6	3:41
7	3:45
8	3:52
9	3:56
10	3:59
11	3:59
12	4:10
13	4:13
14	4:17
15	4:29
16	4:30
17	5:11
18	5:15
19	5:29

(Sprinklers in Test E1)



Operating Sequence	Time (min: sec)
1	2:43
2	3:25
3	3:26
4	3:29
5	3:31
6	3:32
7	3:36
8	3:37
9	3:52
10	3:52
11	3:54
12	4:00
13	4:00
14	4:26
15	4:39
16	5:18
17	5:22
18	5:23
19	7:01

(Sprinklers in Test E2)

FIGURE 11. Sprinkler opening sequence in Tests E1 and E2

SUMMARY AND CONCLUSIONS

The increased frequency of the buildings with high-ceiling clearance, such as atria, airport terminals, hotel lobbies, theaters, and convention halls, renewed concerns over fire protection at such facilities. Recognizing that one of the most practical yet most reliable protection schemes is installing automatic fire sprinklers on the ceiling, two critical issues in designing the ceiling sprinkler system were discussed: (1) whether the sprinklers would actuate with the anticipated fire load? and (2) what type of sprinklers with what discharge density should be adopted to have the system be effective?

Whether a sprinkler would actuate or not depends on the height of the clearance between the fire source on the floor and the sprinkler on the ceiling, the heat release rate of fire, the temperature rating and the response time index of the sprinkler. An early analysis[2] shows how one can assess the sprinkler actuation at a high ceiling with anticipated fire load. It also shows how one can compute the threshold fire size for sprinkler actuation with the given clearance. It shows the differences in the threshold fire sizes depending on whether the exposures are growing 3-dimensional fires or steady 2-dimensional pan fires.

The important design parameters in sprinkler operation are the temperature rating, the RTI, the orifice diameter of the sprinkler, and the discharge density. Data from seven full-scale fire tests[1] conducted under an 18.3 m high ceiling were reviewed to see how the design parameters affect the effectiveness of sprinkler operations. The first two tests were conducted with stacks of the FM Global Class 2 commodity and the other five tests were conducted with stacks of the FM Global Standard Plastic commodity on the floor as the test fire loads. Unlike fire tests in ordinary-clearance facilities, the tests manifested severe sprinkler skipping and made it clear that the sprinkler skipping is one of the most critical factors in determining the effectiveness of sprinkler operations at high ceiling clearance facilities[1]. Thus, the tests reported here provide specific examples of skipping; however, any extension to general conclusions would require more research.

A new parameter, “DIOS” has been used in this work as a way to quantify the severity of sprinkler skipping. Comparing the DIOS values computed for the seven fire tests, what design parameters might reduce the skipping severity and thereby would help bring about the eventual fire control was discussed. The general significance of this parameter beyond the specific use in this work is unknown. It has been used here simply as a convenient means of ranking the severity of skipping. Much additional research will be needed to develop a predictive capability for skipping.

In general, the favorable sprinkler parameters in reducing the skipping severity are a low temperature rating with a fast-response link and a large orifice with a low water pressure. However, specific design parameters have to be determined based on the ceiling clearance and the fire load of each individual facility. It would be highly desirable or even may be necessary finding a way of reducing the severity of sprinkler skipping while providing the discharge density adequate enough for fire control at high ceiling-clearance facilities by applying a similar analysis discussed in this paper.

REFERENCES

1. Nam, S., Braga, A., Kung, H.C. and Troup, M.A., “Fire Protection for Non-Storage Occupancies with High Ceiling Clearances”, Fire Safety Science - Proceedings of the 7th International Symposium, IAFSS, 2003, 493-504.
2. Nam, S., “Actuation of Sprinklers at High Ceiling Clearance Facilities”, Fire Safety Journal, 39, 619-642, 2004.
3. Croce, P. A., Hill, J.P. and Xin, Y., “An investigation of the Causative Mechanism of Sprinkler Skipping”, Fire Protection Engineering, 15:2, 2005.
4. Vincent, B., Personal communication, FM Global, Norwood, MA, USA, 2006.
5. Dundas, P. H., “The Scaling of Sprinkler Discharge: Prediction of Drop Size”, Progress Report No. 10 in Optimization of Sprinkler Fire Protection, Technical Report RC73-T-40, Factory Mutual Research Corporation, Norwood, MA, USA, 1974.