A Case Study: How the Maximum Spacing of Heat Detectors Should Be Determined

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ABSTRACT

The current method of assigning the maximum heat detector spacing based on fire tests comparing the detector responses to that of a sprinkler does not produce clear performance criteria for the tested detectors. The wide variations of the maximum spacing assigned for the same type of detectors among testing laboratories, which is another strong indication of the lack of principle behind the concept developed for the testing method, simply add more confusion. Instead, it is proposed in this paper that the maximum detector spacing should be determined based on a specific mission that is expected to be accomplished by using detectors. An example introduced in this work shows: (1) how that can be accomplished, and (2) how the spacing determined here makes a lot more engineering sense than that determined by the current method.

1. BACKGROUND

Currently, each heat detector is characterized by its temperature rating and its maximum spacing. Measuring the temperature rating of a detector is quite straight forward. In general, oven tests are used for the task. The temperature of air circulating inside an oven, to which a detector sample is exposed, is slowly increased until the sample responds. Since there is very little room for any error and the test itself is quite simple, same results are obtained regardless which testing laboratory conducts the measurement.

The maximum spacing assigned to detectors, however, seldom shows agreements among leading listing organizations. Conceptually, the maximum spacing is the maximum distance from a reference fire that a detector can take while it is expected to respond either equal to or faster than the response expected by a reference detection device that is installed at a fixed distance from the fire. Currently, an ordinary response sprinkler with a temperature rating of 71 ^{o}C is used in the UL test[1], while a sprinkler with a temperature rating close to the temperature rating of the detector under consideration is used in the FM Approvals' test[2]. The reference sprinkler is to be installed at the center of a 3.0 m by 3.0 m spacing. Understandably, the maximum spacing assigned to a detector through these tests can vary widely depending on: (1) test room size, (2) ceiling height, (3) test fire size, (4) test environments such as ambient temperature and humidity, and (5) temperature rating of the reference sprinkler, among other things.

Not surprisingly, there are large variations in the maximum spacing assigned by UL and FM Approvals for identical detectors. The distances assigned by UL tend to be a larger value than that assigned by FM Approvals, mainly because UL conducts the tests in a smaller room than that of FM Approvals while using a larger test fire than that of FM Approvals. It is not uncommon that a detector with a 15-m spacing by UL is given only a 9-m spacing by FM Approvals. In consequence, a detector spacing that is perfectly acceptable to one jurisdiction may not meet the standards of other jurisdictions, depending on what AHJ adopts which standards. The current situation can generate confusion to end users and can create a potentially unpleasant issue in certain fire incident cases.

Even if somehow the tests were standardized to eliminate the confusion surrounding the maximum spacing, still the fundamental question remains. "What does the maximum spacing really mean? Does this guarantee that the detector will respond precisely when it is needed?" No one seems to be able to provide affirmative answers to those questions because the current maximum spacing does not have clear objectives behind it. A more relevant question should be, "What spacing do I need in order for the detector to respond before the fire size becomes larger than *X* kW?" A detector spacing should be mission specific, and should be determined on a case by case basis.

A recent study[3] showed that the response time index (RTI) of heat detectors can be used as a means of assessing heat detectors' thermal response sensitivity to fires. The study also showed how the RTIs can be measured and how the measured RTI values can be utilized to calculate detector response times, provided that either the heat release rate of a fire with respect to time is known or it could be estimated. Thus, the RTI values assigned to detectors would be very handy to answer the questions raised above. By discussing a problem that was encountered recently, this paper intends to show how the maximum spacing of a detector should be determined.

2. DESCRIPTION OF THE PROBLEM AND THE SOLUTION PROCESS

The details of the problem that was asked to be resolved were as follows:

A warehouse, which stores 5.8-m-high-heavy-weight-roll-paper stacks under a 11.6-m high ceiling, is protected by a dry-pipe system equipped with a pre-action valve that is to be tripped by a heat detector. It was requested to determine the largest allowable spacing without compromising the full advantage of the pre-action system.

The main advantage of a detector-tripped pre-action dry-pipe system over an ordinary dry-pipe system is that the pre-action system is to be tripped by a detector well in advance of a sprinkler actuation, so that the system can be ready to discharge water as soon as sprinklers open. A sketch of the feed-main piping system is given in Figure 1 and a sketch of the dry-pipe branch pipe system is given in Fig. 2. As shown in Figure 2, the system consisted of two sets of separate branch lines. The nominal diameter of the branch pipes is 32 mm (1.25 in.) and that of the two cross mains is 76 mm (3 inch). Six sprinklers are attached at each branch pipe, 3.53 m apart each other. The distance between the branch pipes is 2.03 m. Thus, the sprinkler spacing is 3.53 m by 2.03 m. The total volume occupied by compressed air, which is the entire volume shown in Figure 2 including the riser, is approximately 1.03 m^3. The supervisory air pressure of the system is 129 kPa (4 psig). The design static water pressure just below the riser is 894 kPa (115 psig). Thus, under the most ideal situation, approximately 87 % of the dry-air volume can be occupied by water before a sprinkler actuates once the pre-action valve tripped.

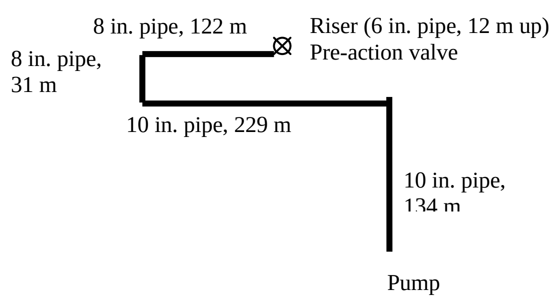

Fig 1. Sketch of the feed-main pipe section of the dry-pipe sprinkler system.

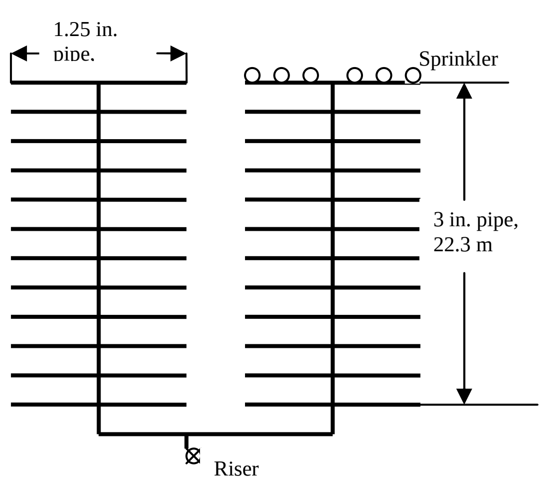

Fig 2. Sketch of the branch lines of the dry-pipe system.

A pre-action system cannot be fully equivalent to a corresponding wet system. The system cannot be filled with 100 % water before a sprinkler actuates because the air inside the system will be compressed and will match the water pressure after all. Besides, if the actuated sprinklers happened to be located where the compressed air pocket is, then the air must be discharged first before any water comes out through the open sprinklers. If those concerns can be set aside, the system with its 87 % volume filled with water before sprinkler actuation is the most one can expect from the given system.

In order to take this advantage, the valve must trip well before a sprinkler actuates so that the system can be filled with water up to its maximum allowable volume when the sprinkler actuates. Thus, the time difference between the response of a heat detector that trips the pre-action valve and the actuation of the first sprinkler must be larger than the time required for the water to fill 87 % of the system, provided that the time required to open the valve completely is negligible. It is, therefore, necessary to find out the response times of the detector and the sprinkler, and the time required for water to fill the system. The following steps will show how those values were obtained.

2. 1 Water Filling Time

The time required for water to fill the 87 % of the dry-pipe volume was computed by using a computer program developed at FM Global Research to calculate the "water delay times" in dry-pipe systems[4]. (The reference 4 and the computer program in it are proprietary; however, a commercially available code [5] can be used for the calculation.) In order to calculate the time required to fill the 87 % of the dry-pipe system with water, details of the piping system, dry-pipe air pressure, and the relation between water flow rates and the water pump pressures must be provided to the program.

The pump performance curve shows that pump pressures were linear to $\dot{Q}_w^{1.85}$, where $\dot{Q}_w$ is the water flow rate in *gpm* and pressure is in *psig*. Table 1 shows a few reference points between the water flow rate and the pump pressure. The computation showed that the time required would be 17 seconds. Thus, the detector must respond at least 17 s earlier than the first sprinkler actuates.

TABLE 1. PUMP PRESSURES VS. WATER FLOW RATES

Water Flow Rate	**Pump Pressure**
0 m^3/s	970 kPa (126 psig)
5.68 x10^{-2} m^3/s (900 gpm)	929 kPa (120 psig)
8.20 x10^{-2} m^3/s (1300 gpm)	888 kPa (114 psig)
1.10 x10^{-1} m^3/s (1740 gpm)	757 kPa (95 psig)

2.2 Sprinkler Actuation Time

The temperature rating of the sprinklers installed on the ceiling of the warehouse is 141 ^oC. The response time index (RTI) of the sprinklers is 234 $(m.s)^{1/2}$. The sprinkler response time with negligible conduction effects can be computed by solving the following equation[6].

$$\frac{dT_e}{dt} = \frac{u^{1/2}}{RTI}(T_g - T_e) \qquad (1),$$

where T_e is the sprinkler heat sensing element temperature, t is time, u is the ceiling flow velocity surrounding the sprinkler, and T_g is the surrounding hot air temperature. In order to solve the above equation, the data of u and T_g with respect to time are needed.

One of the most conservative fire scenarios regarding a pre-action system is that a fire is located directly under a sprinkler, which happens to be at the center of the detector spacing---thereby the most remote location from the surrounding heat detectors. Thus, the sprinkler can actuate at the earliest possible time, while the heat detector would respond at the latest possible time, which would in turn trip the pre-action valve at the latest possible moment. Following the above scenario, the sprinkler is assumed to be located at the fire plume center axis where the elevation is the same as the ceiling clearance height.

The following plume correlations[7] can be used to estimate the centerline temperature and velocity of the plume at the ceiling, if the convective portion of heat release rate (HRR), $\dot{q}_c$, is known.

$$\Delta T_0 = 9.1\left[\frac{(T_\infty)}{(gC_p^2\rho_\infty^2)}\right]^{1/3} \dot{q}_c^{2/3}(z-z_0)^{-5/3} \quad (2),$$

$$V_{z0} = 3.4\left[\frac{(g)}{(C_p\rho_\infty T_\infty)}\right]^{1/3} \dot{q}_c^{1/3}(z-z_0)^{-1/3} \quad (3),$$

where ΔT_0 is the excess temperature at the plume centerline (K), T_∞ is the ambient temperature (K), g is the gravitational acceleration (m/s^2), C_p is the constant pressure specific heat of air (kJ/kg K), ρ_∞ is the density of ambient air (kg/m^3), $\dot{q}_c$ is the convective heat release rate (kW), z is the elevation from the source of the plume, z_0 is the virtual origin of the plume, and V_{z0} is the axial plume centerline velocity (m/s).

In order to solve Eqs. (2) and (3), the heat release rate (HRR) of burning 5.8-m-high, heavy-paper- roll stacks, which are stored in the warehouse, has to be found. Because any direct HRR data from the same fuel were not available, the HRR had to be indirectly estimated by the following way. Old data related to fire tests under a 9.1-m high ceiling that used 5.8-m-high, newsprint-roll-paper stacks as a fuel were located. It was found that the plume axis temperature at the ceiling height in the dada could be expressed as

$$\Delta T_0 = 57(t - 24) \qquad (4),$$

where t is time in second. Then the $\dot{q}_c$ can be obtained by converting Eq. (2) to the following equation,

$$\dot{q}_c = 9.1^{-3/2}\left(\frac{g}{T_\infty}\right)^{1/2} C_p \rho_\infty (z - z_0)^{5/2} \Delta T_0^{3/2} \qquad (5).$$

Inserting Eq. (4) into Eq (5) yields

$$\dot{q}_c = 70\tau^{3/2} \qquad (6),$$

where $\dot{q}_c$ is in kW, $\tau \equiv t - 24$, and z_0 / z is assumed negligible.

Now $\dot{q}_c$ is known, Eq. (2) and (3) will provide u and T_g at the ceiling height [h=11.6 m; z=5.8 m] for Eq. (1), and then a proper numerical integration until T_e becomes the rating temperature will yield the time of the sprinkler actuation. A computational program using a fourth order Runge-Kutta scheme was developed, and it showed that the sprinkler would actuate when t=50 s with an assumption that the ambient temperature was 20 ^{o}C.

2.3 Detector Response Times

A sample of the same type of the detectors that are currently installed at the warehouse, which is shown in Fig. 3, was subjected to the plunge test as described in Ref. 3. The test results indicated that the RTI of the detector was 14 $(m.s)^{1/2}$. The temperature rating of the detector is 57 ^{o}C. Since the RTI value and the temperature rating of the detector are known, the response time of the detector can be calculated with a high precision using Eq. (1), as shown in Ref. 3, once the temperature and the velocity of a fire plume at detector location are known.

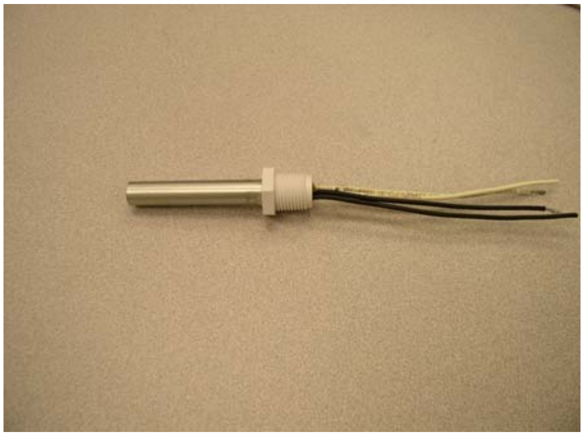

Fig 3. The heat detector currently installed at the warehouse that is the example of the analysis in is work.

The computations were carried out for two cases of the maximum detector spacings, 15.2 m by 15.2 m and 7.6 m by 7.6 m. Following the fire scenario, the detector was assumed to be located at the center of either the 15.2 m by 15.2 m spacing or the 7.6 m by 7.6 m spacing; thus, the detector, which was mounted on the ceiling, was located at either 10.7 m or 5.4 m radial distance away from the fire plume axis. In order to estimate the fire plume velocities and the temperatures at the detector locations, the correlations that show the velocities and the temperatures as a function of a radial distance *r* from a plume centerline need to be known, preferably in functional forms.

Although there are many ceiling flow correlations, new ceiling flow correlations were devised in this work mainly because: (1) the degree of scattering of the data associated with the correlations could be seen at first hand, and (2) many raw data of ceiling flows were readily available. Anyone who does not want to go through developing his/her own correlations, Ref. 8 provides a list of ceiling jet flow correlations and he/she can pick one that seems to be suitable for his/her work.

Fig. 4 shows data of $\Delta T(r)$, the excess ceiling flow temperature at location r, normalized by ΔT_0, which is the excess temperature of an unobstructed fire plume axis at the elevation corresponding to a ceiling height *h*. The radial distance, *r*, was normalized by b, which is a plume half-width of an unobstructed fire plume at the elevation corresponding to the ceiling height *h*. The plume half width can be calculated by[7],

$$b = 0.12\left(T_0 / T_\infty\right)^{1/2}(z - z_0) \qquad (7),$$

where T_0 is $\Delta T_0 + T_\infty$.

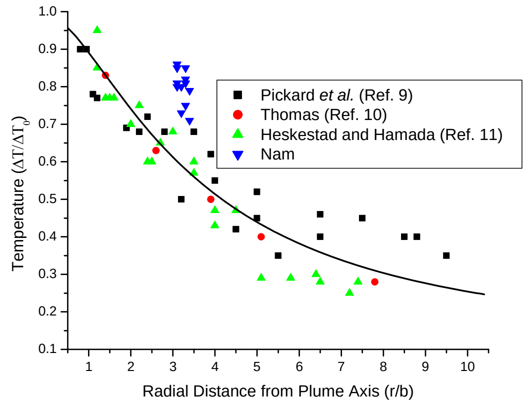

Fig 4. Ceiling flow data of temperature vs. radial distance and a correlation curve.

The data in the figure include the work of Pickard *et al.*[9], Thomas[10], Heskestad and Hamada[11], and Nam. Pickard *et al.* measured ceiling flows generated by alcohol pan fires the diameters of which ranged from 0.15 m to 0.9 m (HRRs varied between 4.85 and 128 kW) under the ceiling heights varying between 1.2 m and 2.4 m. Thomas used 0.42 m diameter alcohol pan fires (HRR=106 kW) under a 1.37-m high ceiling. Heskestad and Hamada used propane burners the diameters of which varied from 0.15 m to 0.61 m (HRRs varied between 11.6 and 382 kW) under the ceilings varying from 0.56 m to 2.5 m high. Nam used heptane *spray* fires ranging from 400 kW to 613 kW under a 4.6-m high ceiling. As the fire plumes from spray fires inherits momentum associated with sprays from nozzles, the temperatures and velocities from Nam's data were expected to be slightly higher than the corresponding temperatures and velocities from the other data sets, which were obtained from purely buoyant fire plumes. The data from Pickard *et al.* and Thomas were converted to fit the normalizations shown in the figure.

A correlation was developed based on the data and is drawn in the figure. The functional form is

$$y = y_0 + \left[a \Big/ \left(w\sqrt{\pi/2} \right) \right] \exp\left\{ -2\left[(x - x_c) \Big/ w \right]^2 \right\} \quad (8),$$

where $y \equiv \log(\Delta T / \Delta T_0)$, y_0=-0.00781, a=-1.2788, w=1.23898, $x \equiv \log(r/b)$, and x_c=1.51005.

Figure 5 shows a collection of data showing $V_r \big/ V_{z0}$ vs. (r/b). V_r is the radial directional flow velocity at r and V_{z0} is the centerline axial velocity of an unobstructed fire plume at the elevation corresponding to a ceiling height h.

The data of Kung *et al.*[12] in the figure are a collection of nine fire tests burning two- to four-tier rack storage of FM Global Class 2 Commodity, which is a double tri-wall carton with metal liner on wood pallet, under a 9.1-m high ceiling for 3 minutes. The ceiling clearances during the tests varied from 1.3 m to 5.9 m and the estimated maximum HRR of each test varied from 8.4 MW to 14 MW. A correlation curve is given in the figure the functional form of which is the same as Eq. (8), however, with different values of the parameters. Here $y \equiv \log(V_r / V_{z0})$, y_0=-0.5514, a=-0.79891, w=0.79131, and x_c=1.31777.

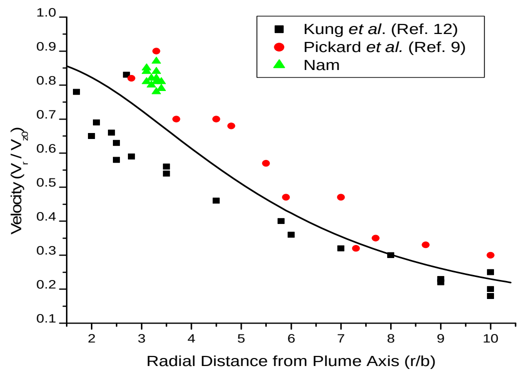

Fig 5. Ceiling flow data of radial velocity vs. radial distance and a correlation curve.

Now all the data necessary to carry out the computations are collected. The temperature and velocity variations with time at r=5.4 m or r=10.7 m can be obtained by applying Eqs. (2) through (8). Then Eq. (1) can be numerically integrated until T_e reaches the detector rating temperature, 57 ^{o}C. The following Table 2 shows the response times of the sprinkler, the detector located at r=5.4 m, which corresponds to the 7.6 m by 7.6 m spacing, and the detector located at r=10.7 m, which corresponds to the 15.2 m by 15.2 m spacing, under various ambient temperatures.

TABLE 2: RESPONSE TIMES OF THE SPRINKLER AND THE DETECTORS

	Response Time (s)		
Amb. Temp. (^{o}C)	Sprinkler Directly above Fire	Detector (7.6 m Spacing)	Detector (15.2 m Spacing)
-7	55	35	42
-1	54	34	41
4	53	34	40
10	52	33	38

16	51	32	37
21	50	31	36
27	50	30	35

Table 2 shows that the time difference between the response from the sprinkler and the response from the detector installed with the 7.6 m by 7.6 m spacing is about 19 seconds. It is larger than the time required for water to fill up the system, which is 17 seconds. Thus, the detectors installed with the 7.6 m by 7.6 m spacing is likely to provide a timely response to open the pre-action valve and in turn it would provide the maximum advantage of the pre-action dry-pipe system. The time difference between the response of the sprinkler and the response of the detector installed with the 15.2 m by 15.2 m spacing, however, is about 13 seconds, which is shorter than the time required for water fill up the system. In consequence, the detector spacing of 15.2 m by 15.2 m is not likely to allow the system to take its full advantage. Our calculation, therefore, indicates that the warehouse in this example should use the 7.6 m by 7.6 m as its maximum detector spacing rather than the 15.2 m by 15.2 m spacing.

Whenever an engineer should make this kind of decision, all the uncertainties associated with the engineering correlations, the experimental data, and the final computational results, should be carefully weighted. Considering other factors relevant to risk analysis associated with fire scenarios would be helpful too.

3. CONCLUDING REMARKS

The current maximum heat detector spacing assigned by listing organizations does not seem to provide clear performance criteria. The maximum distances are determined through fire tests, in which detector samples are spread out with various distances from the source of a fire and the response times are measured. Among the detector samples that respond prior to the response of a reference sprinkler located at 2.2 m radial distance away from the fire source, the distance corresponding to the most remote detector sample becomes the basis for the maximum spacing. Understandably, it would be unlikely that someone can tell with specific engineering terms what the significance of this spacing is. In addition, the test results can vary widely depending on test conditions. In consequence, the maximum spacing even for the same type of detectors seldom agrees among the leading testing organizations, which just add more confusion to end users.

The analysis introduced here shows how the maximum detector spacing was assigned---mission specific and site specific. The example used here is a real case problem that was requested to be solved. The processes used here are quite straight forward and easy to understand, because the decision was made based on a specific engineering problem with a clear objective in the user's mind. The maximum detector spacing in other sites also can be and even, perhaps, *should* be determined following similar processes illustrated in this work---achieving a specific goal by using the detectors.

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