The Skip-resistant Sprinkler Concept – Theoretical Evaluation

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ABSTRACT: This article presents a model for the response time of a sprinkler designed to reduce the skipping phenomenon experienced during large-scale fires. The model guides the design of a cylindrical shield intended to reduce drop impingement from nearby operating sprinklers. Several designs are experimentally tested and shown to reduce likely skipping when compared to the same sprinkler without a shield. The model is validated using a laboratory Plunge Tunnel apparatus to measure the effect of the shield on the thermal sensitivity of the sprinkler and its ability to intercept water drops. This work successfully demonstrates that shielding can decrease the response time of a sprinkler in drop-laden gas flow without causing a substantial increase in response time when exposed to a dry-gas flow. This is the first of two articles on the skip-resistant sprinkler concept. The following article evaluates the performance of the shield in actual fires.

KEY WORDS: sprinkler skipping, sprinkler shield, response time index, thermal response model.

INTRODUCTION

IN AN ARTICLE BY Croce and Hill [1] the sprinkler-skipping phenomenon in large high-challenge fires was analyzed. It attributed the phenomenon to the direct impingement of water drops onto the heat sensing element from nearby operating sprinklers, thereby preventing operation even though local gas temperatures are high. This prevention of sprinkler operation near operating sprinklers reduces the water delivered to the seat of the fire. Virtually all sprinklers can skip under high-challenge conditions. It is natural to ask whether preventing drop impingement from neighboring sprinklers can improve sprinkler system performance.

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This article presents a model to predict the effect on sprinkler response time of a shield designed to prevent drop impingement. Several shield designs are evaluated in a laboratory Plunge Tunnel using both dry and drop-laden heated gas flows.

MODEL FOR RESPONSE TIME OF ANTI-SKIPPING SPRINKLER

The first phase of this study considers the selection of the sprinkler and design of the shield. Base considerations for sprinkler selection are that the sprinkler should be commercially available, well characterized, have several incidences of sprinkler skipping in large-scale fire tests, and have beneficial geometry for easy shield design. An adequate sprinkler shield should have the following attributes: (1) no significant delay of the sprinkler response to the fire; (2) no interference with sprinkler actuation process; (3) negligible impact on sprinkler discharge pattern; and (4) good interception capability of impinging water droplets.

Response of a Sprinkler without Shield

The model helps in the selection of sprinklers that can be shielded and guides the shield design. It builds upon Heskestad and Bill's model [2] for the response of the temperature sensing element (or 'fusible link') of a sprinkler to a flow of hot gas. Their model calculates the response time by considering the convective heat transfer to the link as well as the conductive heat loss from the link to the sprinkler frame. Assuming a dry-gas flow, i.e., gas flow before first sprinkler operation, their model is used for measuring the two parameters that characterize these effects: RTI[1] and the C-Factor[2]. The model considers the effects of convection and conduction. Sprinkler links are usually small enough to allow one to ignore the effects of radiation. The model is extended here to estimate the effect of the shield on the response time of a sprinkler due to the shield impeding the hot gas flow around the thermal link and cooling of hot gases (Figure 1).

The rate of heat addition to the sprinkler link is equal to the heat transfer from the gas to the link minus the heat lost by conduction from the link to the sprinkler frame:

$$m_\ell C_\ell \frac{\mathrm{d}T_\ell}{\mathrm{d}t} = A_\ell h_\ell \left(T_{g\ell} - T_\ell\right) - C'(T_\ell - T_0) \tag{1}$$

[1]Response time index (RTI) is a quantitative measure of sprinkler link sensitivity. Under identical operating conditions, sprinklers with low RTI values are expected to actuate faster that those with high RTI values.
[2]C-Factor is a quantitative measure of the heat loss due to conduction between the heat-responsive element and the sprinkler body. A small C-Factor is desirable.

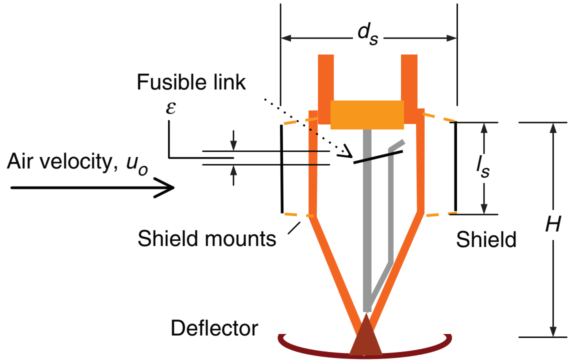

Figure 1. *A quick response sprinkler with shield (The color version of this figure is available online.).*

Dividing by $m_\ell C_\ell$ one has:

$$\frac{\mathrm{d}T_\ell}{\mathrm{d}t} = \frac{T_{g\ell} - T_\ell}{\tau_\ell} - \frac{T_\ell - T_0}{\tau_c} \tag{2}$$

where τ_ℓ and τ_c are respectively the convective and conductive time constants defined by:

$$\tau_\ell = m_\ell C_\ell / h_\ell A_\ell \text{ and } \tau_c = m_\ell C_\ell / C'$$

The heat transfer coefficient of the link, h_ℓ, is given by the Nusselt number $Nu_\ell = h_\ell \ell / k_g$ which is assumed to be proportional to the square root of the Reynolds number for the gas flowing over the link in a fire environment.

$$\begin{aligned} Nu_\ell &= B_\ell (Re_\ell)^{1/2} = B_\ell \left(\frac{u_\ell \ell}{\nu_g} \right)^{1/2}, \text{ so that} \\ h_\ell &= \frac{k_g}{\ell} B_\ell \left(\frac{u_\ell \ell}{\nu_g} \right)^{1/2} \end{aligned} \tag{3}$$

The convective time constant τ_ℓ for the sprinkler is determined both by the RTI of the sprinkler and by the flow velocity u_ℓ of the particular fire environment to which the sprinkler is exposed.

$$\tau_\ell = m_\ell C_\ell / h_\ell A_\ell = \mathrm{RTI}/u_\ell^{1/2} \tag{4}$$

In particular, the convective time constant is inversely proportional to the half power of the gas velocity, u_ℓ, flowing over the link. With this definition, the RTI depends only on properties of air and the sprinkler itself.

$$\mathrm{RTI} = \frac{m_\ell C_\ell}{k_g A_\ell B_\ell} (\nu_g \ell)^{1/2} \tag{5}$$

Also, the conduction time constant;

$$\tau_c = \frac{m_\ell C_\ell}{C'} = \frac{\mathrm{RTI}}{C\text{-Factor}} \tag{6}$$

similarly only depends on sprinkler properties. As long as Equation (3) holds, measured RTI and C-Factor are independent of the fire environment to which the sprinkler is exposed. The RTI and C-Factor parameters are available for virtually all sprinklers [3,4].

Mathematical Solution

Equation (2) can be expressed in dimensionless form as follows:

$$\frac{\mathrm{d}\theta_\ell}{\mathrm{d}t} = \frac{\theta_{g\ell} - \theta_\ell}{\tau_\ell} - \frac{\theta_\ell}{\tau_c} \tag{7}$$

where $\theta_\ell = T_\ell - T_0/T_a - T_0$ is the dimensionless link temperature relative to activation temperature, and $\theta_{g\ell} = T_{g\ell} - T_0/T_a - T_0$ is the dimensionless temperature of gas flowing over the link relative to the activation temperature.

At time $t = 0$ the dimensionless link temperature $\theta_\ell(0) = 0$. The link actuates when $\theta_\ell = 1$ (i.e., $T_\ell = T_a$). If there were no conductive heat loss to the sprinkler frame, the link temperature would eventually approach $\theta_\ell \to \theta_{g\ell}$; however, in the presence of conduction to the frame, the link temperature asymptotes to some lower temperature. This can be seen from the solution of the governing Equation (7), namely:

$$\theta_\ell(t) = \theta_{g\ell} \frac{\tau_1}{\tau_\ell} \left[1 - e^{-t/\tau_1}\right] \tag{8}$$

where

$$\frac{1}{\tau_1} = \frac{1}{\tau_\ell} + \frac{1}{\tau_c} = \frac{\left[u_{g\ell}^{1/2} + C\text{-Factor}\right]}{\mathrm{RTI}}$$

and

$$\frac{\tau_1}{\tau_\ell} = \frac{u_{g\ell}^{1/2}}{u_{g\ell}^{1/2} + C\text{-Factor}}$$

yielding,

$$\theta_\ell = \frac{T_\ell(t) - T_0}{T_a - T_0} = \left[\frac{T_{g\ell} - T_0}{T_a - T_0}\right]\left[\frac{u_{g\ell}^{1/2}}{u_{g\ell}^{1/2} + C\text{-Factor}}\right] \times \left[1 - \exp\left\{-\left[u_{g\ell}^{1/2} + C\text{-Factor}\right]\frac{t}{\text{RTI}}\right\}\right] \quad (9)$$

Figure 2 shows the result for several typical sprinklers. A normal flow velocity without shield might be 3 m/s. A reduction of velocity flowing over the link delays the sprinkler operation – with the possibility that the link will not open for large C-Factors. The final temperature of the link depends on the C-Factor and square root of the velocity flowing over the link, $u_{g\ell}^{1/2}$ while being independent of the RTI.

Cooling of Incoming Gases

The shield itself can cool the incoming gases. It is assumed that the shield is in the form of a strip of height ℓ_s and diameter d_s.

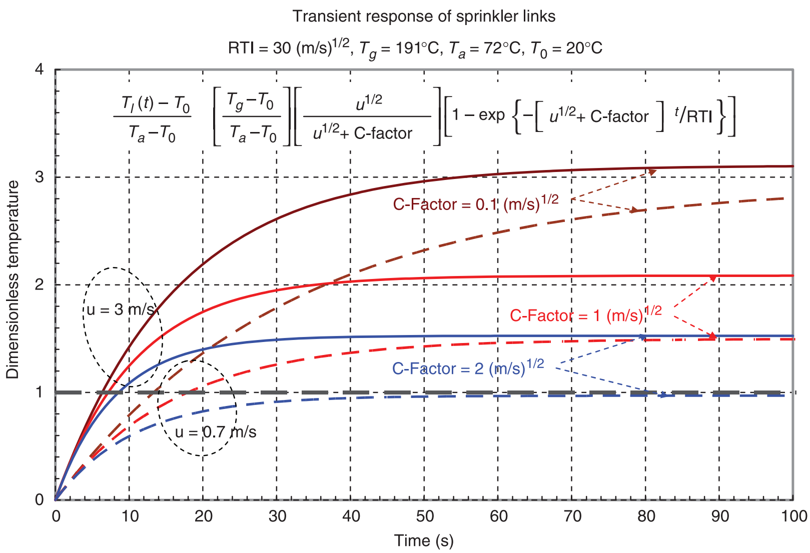

Figure 2. *Response, $\theta_\ell(t)$, of a typical sprinkler without shield (solid lines) for various C-Factors and with suggested shield (dotted lines with gas velocity from Equation (17)) (The color version of this figure is available online.).*

Only heating of the front half of the shield facing the hot gas flow is of concern here.

$$\frac{\pi}{2} d_s \ell_s \delta_s \rho_s C_s \frac{\mathrm{d}T_s}{\mathrm{d}t} = \frac{\pi}{2} d_s (2\ell_s) h_s (T_g - T_s) \tag{10}$$

Dividing through by the coefficients on the left, one has

$$\frac{\mathrm{d}T_s}{\mathrm{d}t} = \frac{T_g - T_s}{\tau_s} \quad \text{or} \quad \frac{\mathrm{d}\theta_s}{\mathrm{d}t} = \frac{\theta_g - \theta_s}{\tau_s} \tag{11}$$

where τ_s is given in the nomenclature. The magnitude of τ_s is of the order of 100s for a 0.25 mm thick stainless steel shield exposed to hot gases flowing at a velocity of 3 m/s. Solving Equation (11), one has:

$$\theta_s(t) = \theta_g[1 - e^{-t/\tau_s}] \tag{12}$$

where θ_s and θ_g are defined by $\theta_s = T_s - T_0/T_a - T$ and $\theta_g = T_g - T_0/T_a - T_0$.

The heat transfer to a strip oriented normal to a flow is given by Jakob [5] as:

$$\frac{h_s d_{\ell s}}{k_g} = B_s \left[\frac{u_g d_{\ell s}}{\nu_g}\right]^{n_s} \tag{13}$$

Multiplying this expression by $k_g/\rho_g C_g u_g d_{\ell s}$ one obtains the Stanton number for the strip:

$$St = \frac{h_s}{\rho_g C_g u_g} = B_s \left[\frac{k_g}{C_g \mu_g}\right] \left[\frac{\rho_g u_g d_{\ell s}}{\mu_g}\right]^{n_s - 1} \approx 0.205 \left[\frac{1}{0.7}\right] \left[\frac{u_g d_{\ell s}}{\nu_g}\right]^{-0.269} \approx 0.027 \tag{14}$$

for a 30 mm high shield and an inflow gas velocity of 3 m/s. The Stanton number depends only weakly on incoming velocity, making it useful for the present analysis. The cooling of the inflowing gases by the shield is:

$$\dot{Q}_{\text{cooling}} = \pi d_s \ell_s (T_g - T_s) h_s$$

where $(2\pi/2) d_s \ell_s$ is the total area of the front and back sides of the shield facing the inflowing gases. This cooling is compared to the total heat supplied by the incoming flow approaching the sprinkler (over height, $H \approx 2\ell_s$, from orifice to deflector):

$$\dot{Q}_{\text{inflow}} = \rho_g u_g C_g (T_g - T_0) H d_s$$

The ratio of these heat flows gives the fractional cooling of the incoming gases, that is:

$$\frac{\dot{Q}_{\text{cooling}}}{\dot{Q}_{\text{inflow}}} = \frac{\pi \ell_s}{H}\left[\frac{h_s}{\rho_g C_g u_g}\right]\left[\frac{T_g - T_s}{T_g - T_o}\right] = \frac{\pi \ell_s}{H} St\left[1 - \frac{\theta_s}{\theta_g}\right] = \frac{\pi \ell_s}{H} St \cdot e^{-t/\tau_s} \leq 0.05 \tag{15}$$

after substituting for θ_s/θ_g from Equation (12) and the Stanton number from Equation (14) while employing dimensions for the sprinkler and shield heights shown in Figure 1. It is clear from the above analysis that the cooling of the inflowing gases is not important and can be ignored. This means that

$$\theta_{g\ell} = \theta_g \tag{16}$$

This minimal cooling implies that the material selected to fabricate the shield does not affect the sprinkler response times.

Blockage of Incoming Gases

The blockage of incoming gases by the shield (and other hardware) can significantly reduce the gas velocity flowing over the sprinkler link. Large blockage would occur for a large shield height to shield diameter ratio, while little blockage would occur for a small shield height to shield diameter ratio. To express this more quantitatively consider the momentum transfer from the outer flow to the flow within the cylindrical volume. The gases flowing over the free bottom surface drive the fluid motion within the cylindrical volume. The rate of momentum transfer is given by the shear stress ρu_g^2 times bottom area, $\pi d_s^2/4$ or $\left(\rho u_g^2\right)\pi d_s^2/4$. Within the cylindrical volume the force is dissipated by friction of the local shear stress, $\rho u_{g\ell}^2$ dragging across all the surfaces within the volume. The total area of dissipating surfaces within the volume is roughly equal to the total interior surface area of the cylindrical volume itself, $\pi d_s \ell_s + (2)\pi d_s^2/4$. Equating both these forces one has:

$$\begin{aligned} &u_{g\ell}^3\left[\pi d_s \ell_s + 2\frac{\pi d_s^2}{4}\right] = u_{g\ell} u_g^2\left(\frac{\pi d_s^2}{4}\right) \\ \text{or} \quad &\frac{u_{g\ell}^2}{u_g^2} = \frac{1}{2 + \frac{4\ell_s}{d_s}} \approx \frac{1}{4} \quad \Rightarrow \quad u_{g\ell} \approx \frac{1}{2} u_g \end{aligned} \tag{17}$$

These arguments are approximate and suggest that the velocity ratio is about 0.5 for the sprinkler and shield shown in Figure 1, which has $d_s \approx 2\ell_s$.

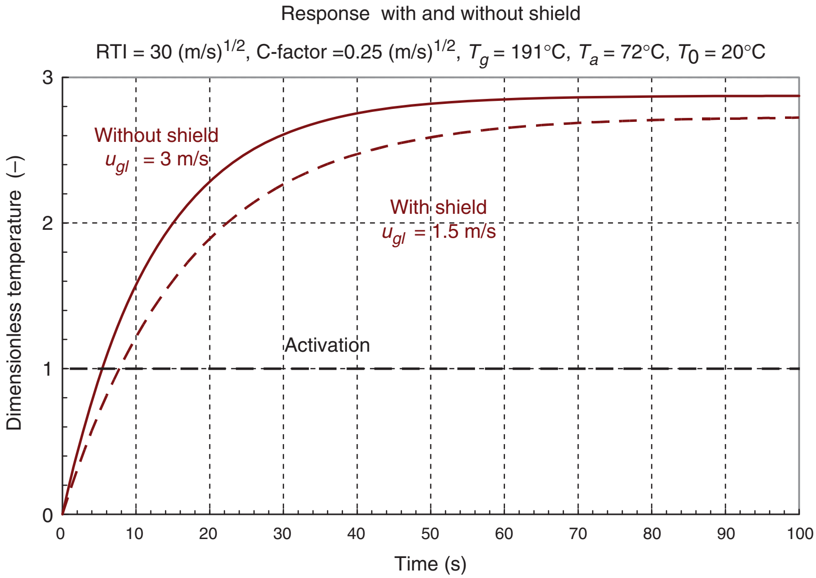

Figure 3. *Predicted response in plunge test with and without a typical shield that reduces the gas velocity as given by Equation (17) (The color version of this figure is available online.).*

Equation (4) says that reducing the velocity by a factor of two should increase the response time by the square root of the velocity ratio – namely by $\sqrt{2}$. The predicted increase in response time is consistent with the plunge test measurements described in the next section. This increase applies only to horizontally moving gases. The suggested cylindrical shield should not impede the upward velocities from a fire directly below the sprinkler; so the response of a sprinkler directly above a fire should not be affected.

Predicted Response – Plunge Test

Based on Equation (17), the link response in a Plunge Tunnel with and without a typical shield can be calculated, as shown in Figure 3 for specific tunnel conditions.

Shield Design Guidelines

There are many practical guidelines for shield design.

1. It is impractical to shield most sprinklers. The sensing elements (glass bulb or fusible link) of most commercial sprinklers cover much of the distance from orifice to deflector. To protect a sensing element from water droplets, the shield needs to extend out beyond the sensing element. Under these

conditions, the shield would effectively block most of the gas access to the sensing element. This suggests the sprinkler shown in Figure 1 is well suited for shielding due to the limited height of its sensing element. Recommendation: $\varepsilon/\ell_s < 0.5$, $\ell_s/H \approx 0.5$, and $0.4 < \ell_s/d_s < 0.5$.

2. It is important that the sensing element be located near the orifice and far from the deflector; so that the shield does not interfere with the water spray pattern coming off the deflector. Recommendation: $H - \ell_s \geq \ell_s$.
3. The presence of a shield reduces the gas velocity flowing over the link. This reduces heat transfer to the link and increases the response time. To minimize the impact it is important for the sprinkler to have a small RTI. Recommendation: RTI < 50 $(\text{m-s})^{1/2}$.
4. The reduction in gas velocity caused by the shield enhances the importance of a low C-Factor limiting conductive heat loss from link to frame (Figure 2). Recommendation: C-Factor ≤ 1 $(\text{m/s})^{1/2}$.
5. Sprinklers are installed with considerable force using a sizeable wrench. To avoid damaging the shield it must have a robust design.
6. The shield only slightly cools the inflowing gases. Therefore, the thermal properties of the shield are unimportant.

VALIDATION OF THE SHIELD DESIGN

Based on the above design considerations, a pendent-style sprinkler with K-factor[3] of 200 L/(minute bar$^{1/2}$) and a fusible link rated at 70°C was selected. Three candidate shield designs were then fabricated based on the design guidelines. The generic shield design consisted of an open-ended thin brass cylinder mounted to the sprinkler frame arms with the sprinkler link centered within the shield. The shields had different combinations of cylinder heights and diameters covering the range of values suggested by the design guidelines.

To establish the effect of the shields on sprinkler response, the Plunge Tunnel was modified to produce both dry and drop-laden-gas flows. The dry gas flow evaluated the shield design on sprinkler response based on the increase in RTI compared to an unshielded sprinkler. The response to the drop-laden heated gas flow evaluated the drop interception ability of the shield.

Setup of the Plunge Tunnel

Figure 4 shows a schematic of the Plunge Tunnel apparatus, including the modifications necessary to produce the drop-laden gas flow. The tunnel was

[3]The K-Factor is a parameter indicating sprinkler nozzle discharge capacity. It is defined as $K = Q/p^{1/2}$, where Q is the water discharge rate (l/minute) and p is the sprinkler nozzle discharge pressure (bar).

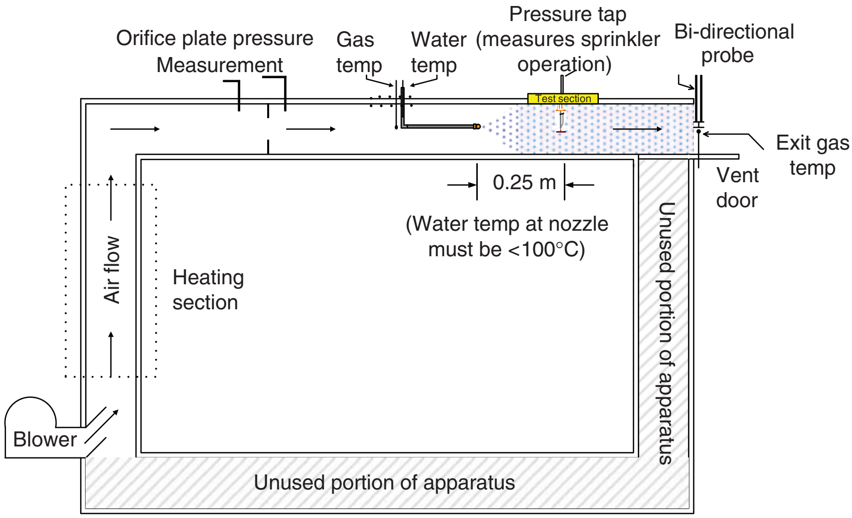

Figure 4. *Side-view schematics of Plunge Tunnel with all modifications (The color version of this figure is available online.).*

operated as an open-loop system by opening the access port immediately downstream of the sprinkler measurement test section. A water spray was introduced into the gas flow using a single nozzle located approximately 254-mm ahead of the sprinkler. This is the minimum distance ahead of the sprinkler that the nozzle could be located and still cover the entire cross section of the tunnel. Flow stabilizing screens located ahead of the test section were removed to allow placement of the nozzle near the test section. The apparatus was otherwise operated under procedures in the test standard [3,4].

The gas velocity in the tunnel was determined both before and after the sprinkler. Before the sprinkler it was inferred from an orifice plate; while downstream of the sprinkler, it was obtained by a bidirectional probe just outside of the tunnel exit. Gas and water temperatures were measured 0.3 m downstream of the orifice plate. Gas temperatures were also measured adjacent to the bidirectional probe. The water spray caused an approximate 20°C temperature drop between these thermocouples. However, this resulted in less than a 0.1 m/s change in the calculated gas velocity.

Water was introduced into the gas flow using a single nozzle located approximately 254-mm ahead of the sprinkler. This is the minimum distance ahead of the sprinkler that the nozzle could be located and still cover the entire cross-section of the tunnel.

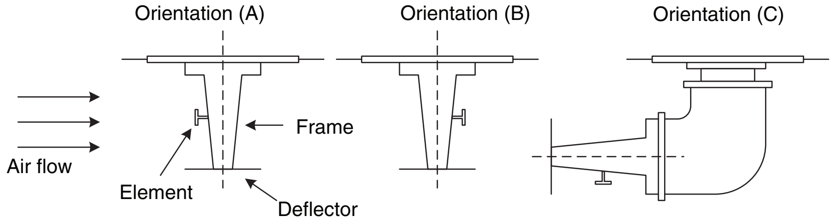

Figure 5. *Sprinkler orientations in Plunge Tunnel tests results.*

Test Conditions

The test matrix consisted of 48 possible configurations, though not all configurations were evaluated due to time constraints. Each test was conducted with a gas velocity of 3 m/s and temperature of 197°C. The configurations for testing were as follows:

- Three sprinkler orientations in the Plunge Tunnel were considered, as shown in Figure 5
- An unshielded sprinkler plus three shield designs
  - Shield B dimensions: 25 mm height × 62.5 mm diameter × 0.27 mm thickness
  - Shield C dimensions: 35 mm height × 70 mm diameter × 0.27 mm thickness
  - Shield D dimensions: 35 mm height × 89 mm diameter × 0.27 mm thickness
- Four gas flow conditions
  - Dry gas flow (normal lab air)
  - Drop-laden-gas flow, seeded with water drops from nozzle discharging at 3.2 L/h. This water discharge was accomplished with a nozzle [6] operating at 2.8 bar, resulting in a ~90 µm average drop size.
  - Drop-laden-gas, seeded with water drops from nozzle discharging at 5.1 L/h. This was discharge was accomplished with a nozzle [6] operating at 6.9 bar, which resulting in a ~65 µm average drop size.
  - Drop-laden-gas, seeded with water drops from nozzle discharging at 5.72 L/h. This water discharge was accomplished with a nozzle [7] operating at 3.1 bar, which resulted in a ~100 µm average drop size.

The above drop sizes are estimates taken from measurements at various pressures. The estimates of drops sizes (±15 µm) can be useful when considering drop motion in the gas flow. More specifically, rough calculations suggested that skipping conditions should occur in a real fire when: (1) gas flow ≥3 m/s, (2) size of drops at a sprinkler's heat sensitive elements is around ~100 µm, and (3) the drop density from nearby sprinklers ~10 drops/cc. It was not possible to maintain all three design conditions due to limitations of the spray formation from these nozzles. Instead, only the specified gas velocity and drop size were maintained, while the drop density generally exceeded a wet flow seeded at 5.72 L/h.

Plunge Tunnel Test Results

A total of 147 tests were conducted in a hydraulics laboratory at the FM Global Research Campus, RI USA. Sprinkler operation times for each configuration and corresponding RTI values are shown in Table 1. With the exception of the wet tests having 3.2 L/h of water, each test configuration consisted of at least two tests. Each dry gas test configuration consisted of at least five tests. Cells containing only a 'dash' indicate configurations that were not tested.

For Plunge Tunnel testing, it is presumed that skipping would have occurred if the water drops prevented sprinkler operation or substantially delayed (>60s) operation compared to a dry gas flow. For real fire scenarios, skipping conditions generally occur when the source fire overpowers the protection system. The result is that water drops from the initial sprinklers become entrained in the hot gas flow and impact the heat sensitive link of neighboring sprinklers, substantially delaying, or even completely stopping, their operation.

Table 1. Sprinkler operations times.

	Gas flow	Dry		Wet (3.2 L/h)	Wet (5.1 L/h)	Wet (5.72 L/h)
Sprinkler orientation	**Shield**	**Operation time**	**RTI**	**Operation time**	**Operation time**	**Operation time**
See Figure 5	none, B,C,D	s	$(m\text{-}s)^{1/2}$	s	s	s
A	None	3.9	27	5.0	6.2	∞
	B	4.8	33	6.5	7.0	8.0
	C	6.0	42	7.0	–	–
	D	5.5	38	6.5	7.7	7.7
B	None	4.0	28	4.8	7.7	∞
	B	5.4	37	–	8.1	10.4
	C	5.5	38	–	–	–
	D	5.2	36	6.9	8.4	9.1
C	None	4.6	32	6.0	–	10.2
	B	4.8	33	–	–	30.9
	C	4.9	34	–	–	–
	D	5.1	35	6.5	–	26.8

Conclusions from Plunge Tunnel Testing

Comparison of Figure 3 and Table 1 shows that model predictions are consistent with testing results. The following conclusions derived from the test data highlight the potential of a shielded sprinkler to reduce skipping in a real fire scenario without an excessive increase in the sprinkler's RTI:

1. In a dry gas flow with the sprinkler deflector oriented towards the flow (Orientation C), the presence of shield 'B' and 'D' resulted in an approximate 5% increase in the RTI. This configuration simulates the operation of the first sprinkler from a fire source directly below the sprinkler.
2. In a dry gas flow the presence of shield 'B' and 'D' resulted in an approximate 30% increase in the sprinkler's RTI when the sprinkler arms were oriented normal to the gas flow (Orientations A and B). This configuration simulates subsequent sprinkler operations (i.e., not the first operation) in a nonskipping fire scenario.
3. The more compact shield design 'C' was generally slower than shields 'B' and 'D'. Model predictions would say that this more compact design further reduces the gas velocities within the shield causing a reduction in heat transfer to the link. Therefore, shield design 'C' received only limited testing.
4. Seeding the gas flow with 5.72 L/h resulted in a condition where the unshielded sprinkler did not operate when the sprinkler arms were oriented normal to the gas flow (Orientations A and B). However, when equipped with shield 'B' and/or shield 'D' the sprinkler operated $\leq$10s. This configuration simulates subsequent sprinkler operations (i.e., not the first operation) in a skipping fire scenario and provides positive evidence that the shield is effective at intercepting water drops without blocking the hot gas flow necessary for proper operation of the link.
5. The RTIs of the sprinkler/shield combination for both shield 'B' and shield 'D' fell nominally within the guidelines for an ESFR sprinkler (RTI between 19 and 36 $(m\text{-}s)^{1/2}$) [8].
6. The percent increase in the sprinkler RTI with increasing water seeding in hot gas flow was slightly less for shield 'D' than for shield 'B'.

Based on the results of this testing, shield 'D' exhibited the best combination of performance in a dry gas flow and performance in a wet gas flow. This shield was selected for intermediate- and large-scale testing as described in the accompanying article [9].

NOMENCLATURE

A_ℓ = Total exposed surface area of link (m^2)
B_ℓ = Coefficient Nusselt number expression (–)
B_s = 0.205 Coefficient for Jakob's Nusselt number expression for shield (–)
C_ℓ = Specific heat of link (kJ/kgK)
C_s = Specific heat of shield (kJ/kgK)
C' = Coefficient for conduction to frame (kW/K)
C-Factor = RTI $C'/m_\ell C_\ell$characterizing conduction from link to frame [$(m/s)^{1/2}$]
d_s = Diameter of shield (m)
$d_{ls} = 2\ell_s/\pi$, Diameter of cylinder having same surface area as strip (m)
H = Height of sprinkler from orifice to deflector [m]
h_s = Heat transfer coefficient for shield (kW/m^2K)
h_ℓ = Heat transfer coefficient for link (kW/m^2K)
k_g = Thermal conductivity of gas (kW/mK)
ℓ = Characteristic size of link (m)
m_ℓ = Mass of link (kg)
$Nu_\ell = h_\ell \ell / k_g$, Nusselt number for heat transfer to link
$Nu_s = h_s d_{\ell s}/k_g$, Nusselt number for shield (–)
n_s = 0.731, Exponent for Jakob's Nusselt number expression (–)
$\mathrm{Re}_\ell = u_\ell \ell / v_{g\ell}$, Reynolds number for flow over link
$Re_s = u_g d_{\ell s}/v_g$, Reynolds number for shield (–)
$\mathrm{RTI} = \tau, u_\ell^{1/2}$, Response Time Index of Sprinkler $(m\text{-}s)^{1/2}$
$St = h_s/\rho_g C_g u_g$, Stanton number for shield (–)
$T_{g\ell}$ = Temperature of gas flowing over link (K)
T_ℓ = Temperature of link (K)
T_a = Sprinkler link activation temperature (K)
T_g = Temperature of gas impinging on shield (K)
T_s = Temperature of shield (K)
T_0 = Temperature of ambient (K) Greek
δ_s = Thickness of shield (m)
ε = Height of sensing element (m)
$\mu_g = \rho_g v_g$, Dynamic viscosity of gas (kg/ms)
ρ_s = Density of shield (kg/m^3)
v_g = Kinematic viscosity of gas flowing over link
$\tau_c = m_\ell C_\ell / C'$, Link conduction time constant (second)
$\tau_\ell = m_\ell C_\ell / h_\ell A_\ell$, Link convective time constant (second)
$\tau_s = \rho_s C_s \delta_s / 2h_s$, Thermal response of shield (second)
$\theta_{g\ell} = (T_{g\ell} - T_0)/(T_a - T_0)$, Dimensionless gas flowing over link temperature (–)

$\theta_\ell = (T_\ell - T_0)/(T_a - T_0)$, Dimensionless link temperature (–)
$\theta_g = (T_g - T_0)/(T_a - T_0)$, Dimensionless incoming gas temperature (–)
$\theta_s = (T_s - T_0)/(T_a - T_0)$, Dimensionless link temperature (–)

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