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FRS RAMP TEST FOR THE THERMAL SENSITIVITY OF SPRINKLERS

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SUMMARY

This paper describes the engineering approach adopted at the Fire Research Station to investigate sprinkler behaviour using ramp tests. Comparisons are drawn between the parameters derived using two basic methods, i.e., ramp and plunge tests, for evaluating sprinkler sensitivity. The use of the ramp test for deriving characteristic sprinkler parameters and for broad classifications is illustrated. Additionally, evidence is presented that the proportion of heat loss by conduction from a sprinkler element may vary over the range of 6 heating rates typically employed in the rate of rise test. This fact alone may justify the precautionary need to perform a limited number of rate of rise tests to confirm a sprinkler's capacity to function correctly in reasonably unfavourable yet realistic conditions. The work is aimed primarily to meet the needs of the sprinkler industry.

INTRODUCTION

The Fire Research Station is currently investigating the thermal response of sprinklers[1-4] to assess their suitability for both life safety use and for the protection of high value high racked storage. The sprinklers needed for life safety must respond more rapidly than the sprinklers traditionally used for conventional property protection, i.e., before significant spread occurs and well before flashover, in order to minimise the hazards arising from flames and smoke. Fast response sprinklers may also be required for the protection of goods stored in high racks since it has been shown that the vertical spread of fire in racks may be rapid and can by-pass traditional sprinklers of slower response[5].

Methods for measuring the thermal sensitivity of sprinklers are needed for classifying performance and for assessing their suitability for specific applications. These methods must be realistic and produce results which are appropriate to the heating conditions encountered when fast response sprinklers are required to operate in practice.

APPLICATIONS FOR FAST RESPONSE SPRINKLERS

Fast response sprinklers for life safety may be required for patient health care areas in hospitals, for institutions and in homes for the elderly where occupants may be unable to help themselves in the event of a fire. They may also be needed for buildings of public access such as hotels, shops, theatres, leisure centres and complex developments containing all or some of these. Although the people concerned may be mobile they are frequently unfamiliar with the building layout and escape routes. These sprinklers have been mandated for the residential protection of one and two family dwellings in the USA[6]. Fast response sprinklers can also provide enhanced protection for the specialised property risk posed by the storage of high value strategic goods in high racks in warehouses up to 20m high. Hence any realistic test of sprinkler sensitivity for these applications should include both the fast and slow heating rates which are likely to be associated with the fuel loadings normally found in high-hazard industrial and 'life-safety' type occupancies respectively.

THE PROBLEM

The concept of using sprinklers for life safety is a comparatively recent application for sprinklers, but they have been used for protecting property for about 100 years. In this, they have proved generally successful but during this period large fires have occurred in sprinklered premises. The recent introduction of mechanical handling has allowed storage space to be used more intensively by stacking goods in tall racks which extend up almost to roof level. Once fire reaches the top of a stack, subsequent fire spread horizontally could become extremely rapid and quickly

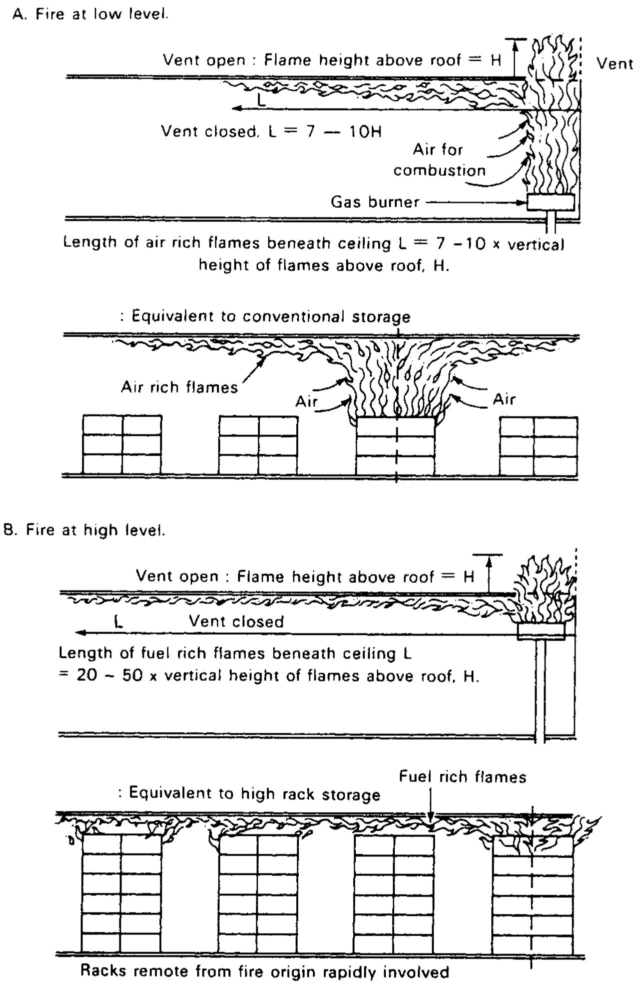

Figure 1. Horizontal length of flames below ceiling equivalent to vertical height of flames above roof for fires burning at high and low levels.

involve most or all of the building. This phenomenon was examined at FRS in a research programme investigating the contribution of ceiling flames to fire spread in compartments[7] and it was demonstrated that for fires burning at low level, the horizontal length of flames below the roof exceeded the vertical height of flames above the roof by a factor of 7, Figure 1. The corresponding figure for flames generated at high level may exceed a factor of 40 for fuel-rich flames which can rapidly involve the upper regions of racks remote from the original fire. Long fuel-rich flames at high level have been witnessed during an industrial fire[8].

Thus sprinklers intended for high rack use should be capable of quickly controlling and locally confining any outbreak of fire within the rack thereby preventing significant burning at high level.

Factors to be Considered in Sprinkler Tests

Operating and Test Conditions

The pattern of fire growth likely to occur in life safety and high rack situations is shown schematically in Figure 2. The initial stage A-B represents the combustion of the material first ignited during which the fire may develop relatively slowly until, for example, a larger item or the main fuel becomes involved at point B. The air temperature then increases rapidly, often with the square, cube or exponential function of time. The transition stage B has often occurred at a relatively low air temperature in the region of 100°C. For fuels in which fire develops rapidly the characteristic ABC may form a continuous curve.

Fast response sprinklers should preferably operate before point B is reached, i.e., while air temperatures and gas velocities are low.

The following factors must be taken into account when designing test methods for measuring the thermal response of sprinklers if these methods are to be realistic and representative of those produced when fast response sprinklers are required to operate.

1.) Fast response sprinklers should operate while the fire is still small, i.e., before large

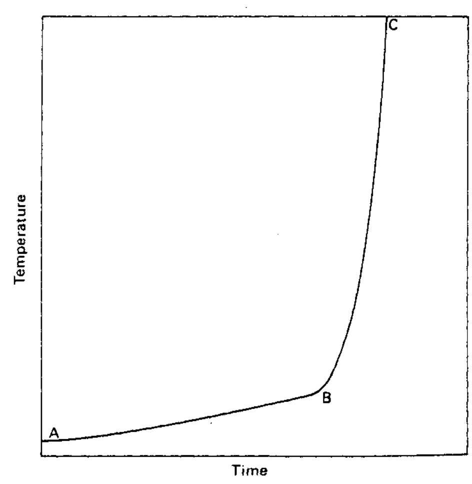

Figure 2. Fire growth in life safety and high rack situations (schematic).

radiative flames are formed. The solid angle subtended by the fire at the sprinkler is very small and heat transfer to the sprinkler is predominantly by convection.

2.) Sprinklers are usually screwed into a network of water-filled pipework to which the sprinkler may lose heat by conduction prior to operation in a fire. During this period the sprinkler may lose heat by radiation to the surroundings which remain at or closer to the initial ambient temperature.

3.) The initial rate at which any fire will develop is unpredictable because it is dependent upon many factors. In a realistic test, the operational characteristics for sprinklers should therefore be measured using a repeatable range of heating rates representing various rates of fire development. The philosophy of the rate of rise test originally developed for heat-sensitive fire detectors[9] is equally appropriate for sprinklers.

4.) Typical velocities of between 1 and 4 m/s have been measured in the layer of hot gases flowing beneath the ceiling during the early stages of fires in compartments[10]. The gas velocity has tended to increase from the lower value of 1 m/s to a velocity approaching 4 m/s as the fires developed. Sprinklers which are required to operate early in a fire should therefore preferably be tested for response at airstream velocities nearer the lower value. The vertical gas velocities in the flues between high racks are also likely to be low during the earliest stages of fire development.

Sprinkler Position and Orientation

Tests for measuring the thermal response characteristics of sprinklers should include the salient features present in practice. Fast-response sprinklers are required for the two main purposes of life safety and high rack protection: these two sets of operating conditions are basically different.

Sprinkler position relative to gas flow

In life safety situations the sprinklers are usually subjected to relatively favourable conditions for normal heat transfer to the element from the lateral flow of hot gas layer beneath a ceiling whereas pendant mounted in-rack sprinklers operate as a result of a rising vertical hot plume meeting the sprinkler end-on. In the latter case, the deflection of the hot gas flow away from the sensing element by the hydraulic deflector may

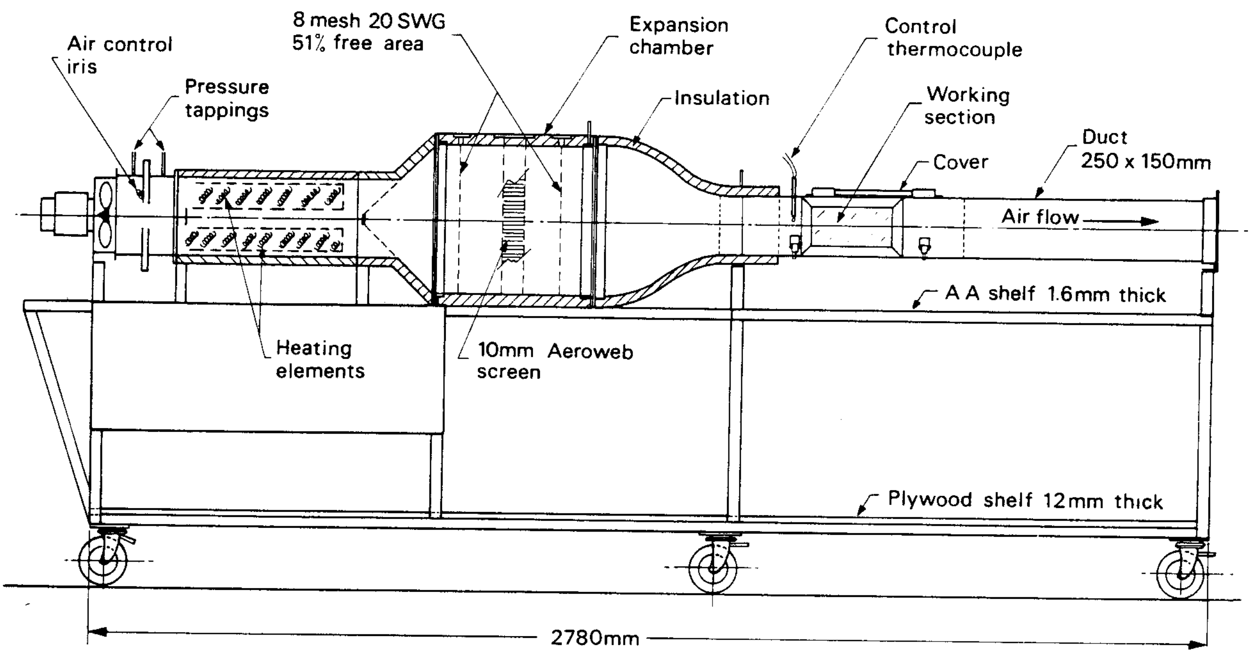

Figure 3. FRS heated wind tunnel.

result in significant differences in response times for sprinklers tested in the "flue" position compared with those obtained in the layer position.

Sprinkler orientation relative to gas flow
Differences in response times in the layer position may also arise from the screening effect due to the frame of the sprinkler deflecting hot gas away from the element at various orientations. Sprinkler frames having higher values for their width/thickness ratio will cast a relatively wide thermal shadow. The effect of this will be greatest for sprinkler frames which are appreciably wider than the exposed operating element.

Heated Wind Tunnel

In order to accurately measure the thermal characteristics of sprinklers it is necessary to use a sophisticated heated wind tunnel; such a tunnel has recently been designed and constructed by FRS[1] to reproduce the required operating and test conditions described previously *(Factors to be Considered in Sprinkler Tests)* as closely as possible.

Wherever possible commercial components have been used in the tunnel, which is required to operate reliably for long periods, Figure 3. The components include a continuously rated fan, an iris-type variable shutter to control air velocity and a 3-phase 18 kW industrial (convection) heater. The power supply to the heating elements is programmed and controlled by commercial units responding to the output of a fine wire (0.12 mm diameter) thermocouple positioned in the entry to the working section.

The tunnel's measurements are 2.8 m long, 1.1 m high by 0.7 m wide. It is made from 1.6 mm thick aluminum sheet and its resulting low thermal mass and short time constant normally enable the tunnel air temperature to respond to programmed changes in temperature within about 10 seconds. The walls of the working section were not insulated in order to assist cooling. Their low emissivity (ε = 4-7% for aluminum) and the fact that their temperature remains significantly below that of the element of the sprinkler under test in all rate of air temperature rise conditions precludes an overall heat transfer to the element by radiation. Sprinklers may, however, lose heat by radiation to the walls of the tunnel.

Performance of Wind Tunnel
Linear rates of air temperature rise varying from 1-60°C/min may be maintained up to a maximum temperature of 200°C in the working section of the tunnel. The maximum temperature may be increased to 250°C for rates of rise ranging from 1-30°C/min. The tunnel has been operated at up to 300°C for short periods.

The air velocity in the working section is monitored using a micromanometer permanently connected across the variable shutter and may be varied from 0.8 to 1.5 m/s at 25°C. The tunnel is a constant mass flow device hence the velocity varies predictably with temperature and produces conditions which are reasonably representative of those produced in the early stages of fire development. The tunnel is suitable for carrying out both "rate of rise" and "plunge" tests.

Thermal Characteristics of Sprinklers

The characteristics[1] most frequently used to define the thermal response of a sprinkler are the nominal release temperature θ_{nom}, the effective operating temperature θ_E, the sprinkler time constant τ and the response time index *(RTI)*.

Nominal Release Temperature *(θ_{nom})*

Currently, the nominal release temperature (θ_{nom}) is specified by a test method meeting with Fire Offices' Committee (FOC) approval. In this test sprinklers are placed in a stirred liquid bath and the liquid temperature slowly increased at about 0.5°C/min until they operate. The nominal release temperature derived from these results represents the maximum ambient temperature which the sprinkler will withstand without operating when the sprinkler and its associated pipework are in thermal equilibrium with the surroundings. The nominal release temperature is most appropriate for quasi-static conditions where small changes in temperature occur relatively slowly.

Effective Operating Temperature (θ_E)

The effective operating temperature θ_E is the minimum airstream temperature required to cause sprinkler operation in non-equilibrium conditions and is derived from rate of rise test results. The effective operating temperature is applicable to dynamic conditions where temperature changes allow heat losses from the sprinkler element to its mounting frame to become significant compared with the rate of heating of the element.

Time Constant (τ)

The time constant τ for an element is normally defined as the ratio mc/hA where mc is the thermal mass of the element (mass x specific heat) and hA is the product of the heat transfer coefficient and the surface area available for heat transfer. Thus the temperature of a sprinkler having a short time constant of 30 s will lag behind a linearly rising air temperature by a period of 30 s and will operate 60 s before an otherwise identical sprinkler having a longer time constant of 90 s. The physical significance of time constant with respect to test methods is described under *Principles of Test Methods*.

Response Time Index (*RTI*)

The value of the time constant is dependent upon the convective heat transfer coefficient which varies with the square root of the airflow velocity, $u^{1/2}$. The *RTI* is the value for time constant at a gas velocity of 1 m/s and is defined as $\tau\, u^{1/2}$. This compensates for changes in the value for time constant measured at differing airflow velocities.

PRINCIPLES OF TEST METHODS

The test methods commonly used for measuring the thermal sensitivity of sprinklers are the rate of rise test developed at FRS (UK)[1] and the plunge test developed by FMRC (USA)[12]. Both methods employ heated wind tunnels. The initial fire growth rates for both life safety and property protection applications are unpredictable and may vary from slow to rapid depending upon the specific circumstances involved. The rate of rise test aims to reproduce a realistic set of initial fire conditions by subjecting sprinklers to rates of air temperature rise ranging from 2 to 30°C/min.

The "plunge" test represents a convenient

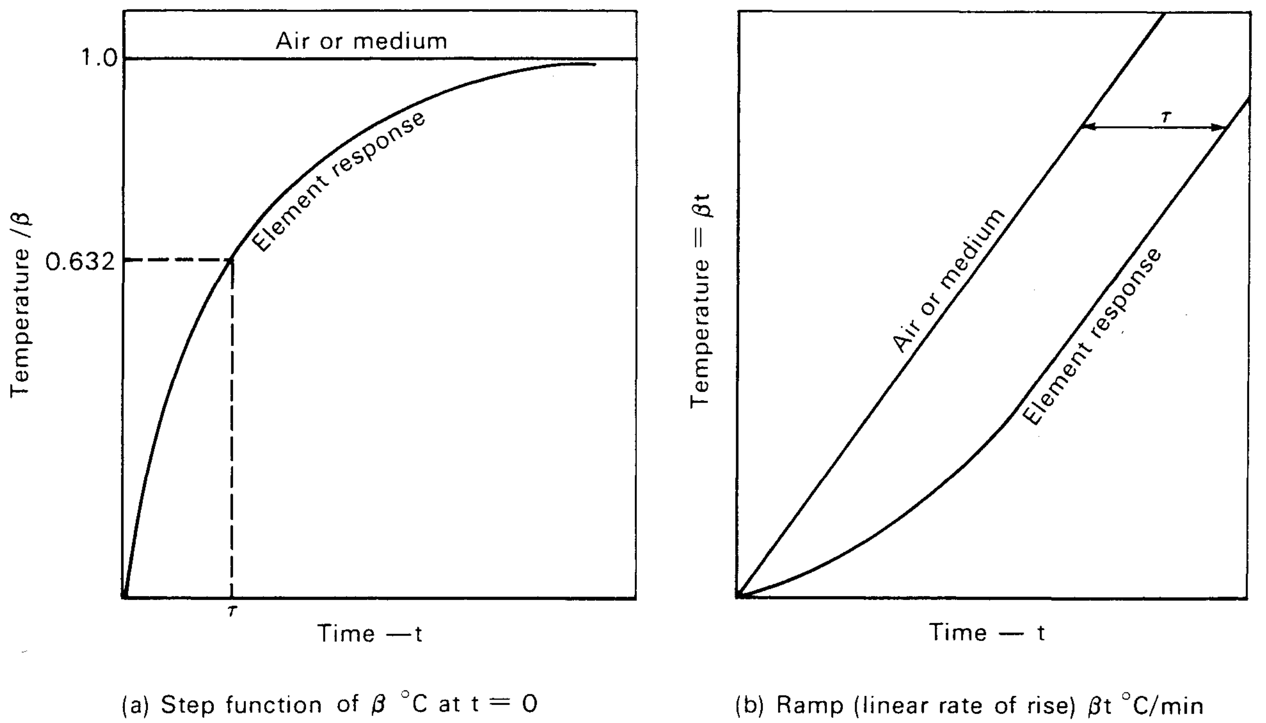

Figure 4. Physical significance of time constant *(t)* for plunge test (a), and rate of rise test (b) for an element experiencing no heat losses.

means for monitoring sprinkler response by measuring the time to operate when a sprinkler is "plunged" into a flowing hot airstream. The results of this test are used to calculate the sprinkler time constant which is appropriate to rapid heating conditions.

The significance of time constant for both rate of rise and plunge test conditions is shown, Figure 4.

Rate of Rise Test

This procedure is used to determine both the effective operating temperature θ_E and the time constant τ for a sprinkler. A sprinkler is attached to the cover plate and placed in the working section of the wind tunnel operating at an initial airstream velocity of 1 m/s measured at 25°C. The tunnel air temperature is increased at 5°C per minute from ambient to the "start" or conditioning temperature θ_S of 30°C at which the sprinklers are "soaked" for 5 minutes. The tunnel air temperature is then increased at one of a series of linear rates of rise in air temperature β ranging from 2 to 30°C/min. The hot gas temperature at operation and the time to operate measured from the start of the ramp are noted. The sprinkler time constant and the effective operating temperature are derived using linear regression from the results using the equations below.

When a sprinkler is immersed in a flowing airstream the temperature of which is increased at β°C per minute, the hot gas temperature at sprinkler operation (θ_g) is, in its simplified form (ignoring exponential transients for the case when t is sufficiently large, i.e., $t > 3\tau$)

$$\theta_g = \theta_E + \beta\,\tau \qquad (1)$$

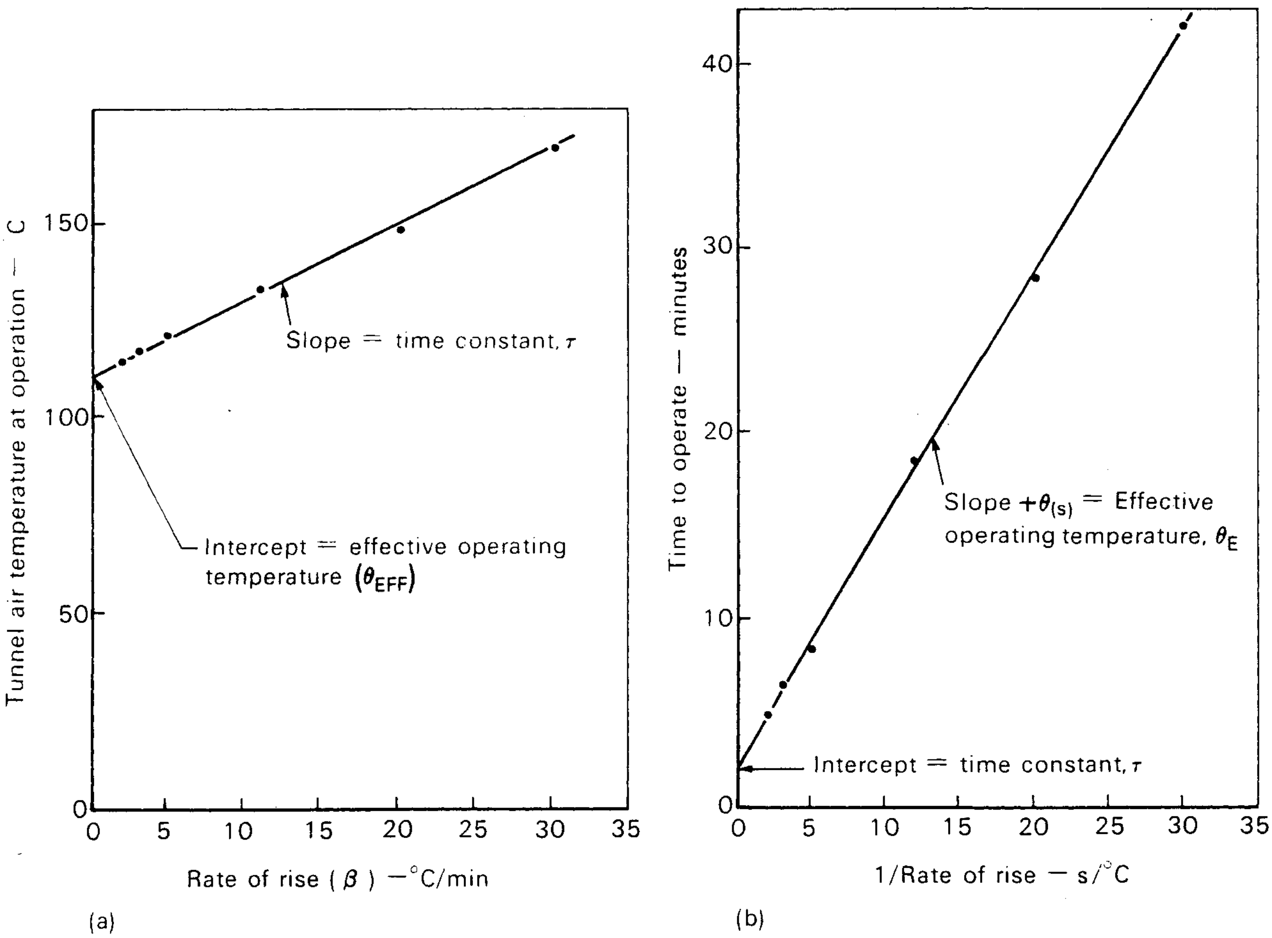

Figure 5. Determination of effective operating temperature (θ_E) and time constant (τ) from rate of rise test results.

where

θ_g = tunnel air temperature at operation
θ_E = effective operating temperature of sprinkler
β = rate of change in tunnel air temperature

The full equations have been discussed elsewhere[4].

A graphical plot of θ_g against β should give a line whose slope is the time constant τ and which has an intercept (where $\beta = 0$) equal to θ which is the minimum air temperature required for operation in dynamic fire conditions, Figure 5. The time taken for the sprinkler to respond, t, is

$$t_r = \frac{\Delta\theta}{\beta} + \tau = \frac{\theta_E - \theta_s}{\beta} + \tau \qquad (2)$$

where $\Delta\theta$ = temperature rise of gas above initial value, θ_s.

A graphical plot of t_r against $1/\beta$ should produce a line whose slope is $\Delta\theta$. θ_E is obtained when the starting temperature is included, i.e., $\Delta\theta$ + θ_s = θ_E. The intercept is the time constant (when $1/\beta = 0$), τ, Figure 5.

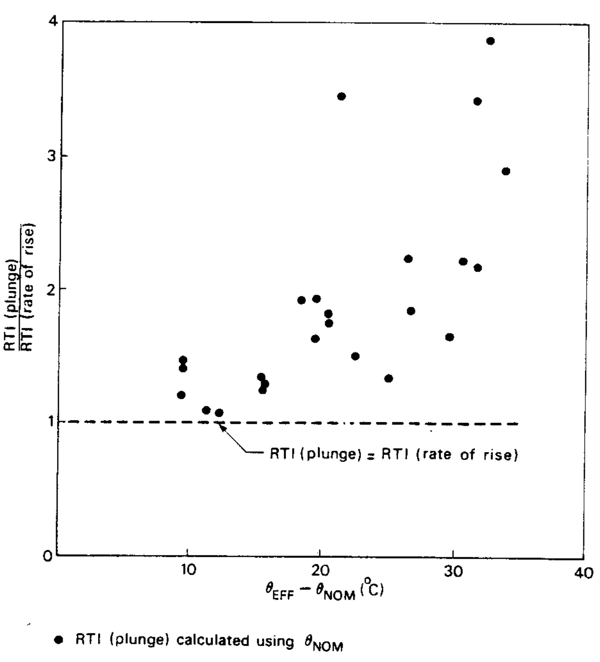

Figure 6. Summary of experimental results showing the ratio of the RTI values measured in the rate of rise and plunge tests.

'Plunge' Tests

The 'Plunge' test was developed at FMRC[12] and recently extended to take account of heat losses[13]. Sprinklers are normally conditioned at the ambient temperature θ_A in the laboratory. Sprinklers are mounted and then plunged into the hot tunnel operating at an airstream temperature, θ_g, of 135°C and velocity, u, of 1.5 m/s. The hot gas temperature of 135° was selected for this work (a) from precedent and (b) because it is similar in magnitude to the higher gas operating temperatures reached during rate of rise tests at the higher values for β. The conditions for heat transfer in the plunge tests are therefore broadly comparable to those obtained in the "rapid" rate of rise tests. Unless the walls of the tunnel working section are refrigerated, they tend to attain a temperature approximately equal to 50% of the hot gas temperature. Hence in plunge tests, sprinklers are additionally heated by radiation from the tunnel walls prior to operation. Sprinklers which are susceptible to radiation effects may therefore operate sooner than expected.

The sprinkler time constant, τ_{nom}, is calculated for these conditions using

$$\tau_{nom} = \frac{-t_r}{\ln\left(1 - \frac{\Delta T_L}{\Delta T_g}\right)}$$

where $\Delta T_g = \theta_g - \theta_A$, $\Delta T_L = \theta_{nom} - \theta_A$ and t_r is the time to operate. The effective operating temperature may be used to calculate an alternative time constant (τ_E) using ($\theta_E - \theta_A$) for the value of ΔT_L[2,4].

Comparisons Between Test Methods

In order to compare the two test methods response time indices have been derived from both rate of rise and plunge test methods for a selection of sprinklers. The results are for sprinklers tested "dry" with the sprinkler axis perpendicular to the air flow and in the most favourable orientation with yoke arms across the airflow.

Two values were calculated for the *RTI* (plunge) viz. RTI_{nom} and RTI_E ($\tau_{nom}u^{1/2}$ and $\tau_E u^{1/2}$ respectively) for comparison with the corresponding value for the *RTI* derived using the rate of rise test, RTI_R. The ratio of RTI_{nom}/RTI_R is shown plotted against ($\theta_E - \theta_{nom}$), Figure 6. Large differences, in some cases in terms of a factor of 2-4, are produced, usually for sprinklers with longer time constants for which the difference between the "effective" and "nominal" temperatures exceed about 25% of the nominal rating. These differences are mainly attributable to the use of θ_{nom} to determine thermal characteristics for sprinklers when subjected to dynamic heating conditions in a hot gas medium where thermal losses occur. The discrepancies between the results of both test methods are considerably reduced when the effective operating temperature θ_E measured for this sprinkler in the rate of rise test is used to calculate response time indices for the plunge test. The corresponding data calculated using θ_E are shown plotted in Figure 7. Most of the results are close to a value of unity at which *RTI* (plunge) equals *RTI* (rate of rise) and the scatter is significantly reduced with about 70% of the points within the range 0.7 to 1.2 and 30% outside this range. The original plunge test process has been subsequently modified[13] to enable velocity independent parameters (*RTI* and constant conductivity factor) to be determined using a series of relatively low temperature plunge tests. Corresponding values for *RTI* and conductivity factor can be readily calculated from the values of τ and θ_E derived from the rate of rise tests[14]. Although equivalent, they are not necessarily identical as discussed in the Discussion Section.

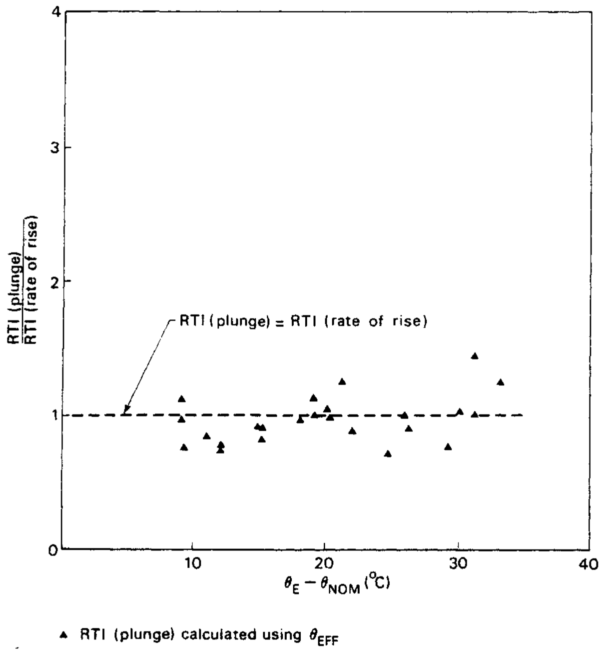

Figure 7. Summary of experimental results showing the ratio of the plunge and rate of rise *RTI* values based on effective operating temperature.

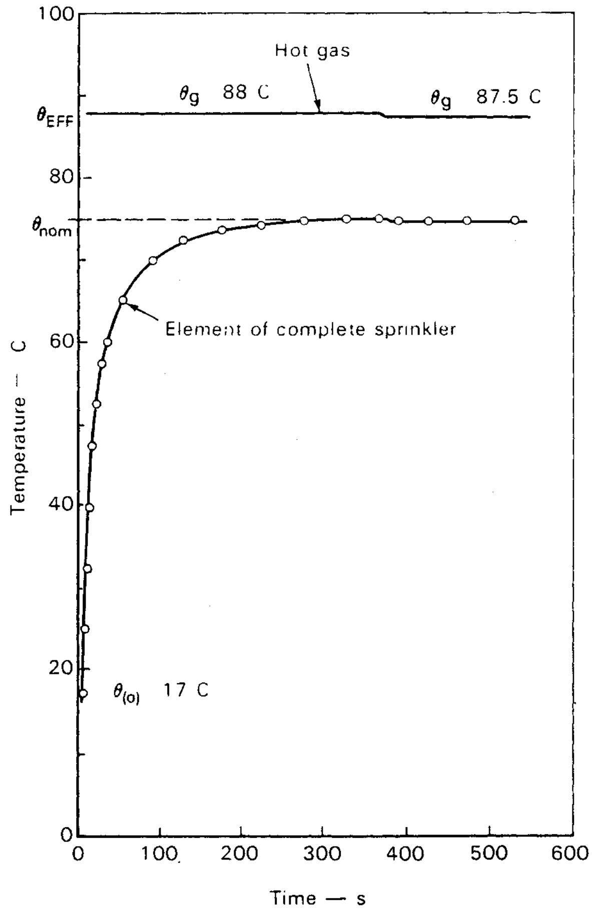

Figure 8. Link temperatures: plung test (wet) at q_E.

Confirmation of Effective Operating Temperature for a Fast Response Sprinkler

The premise that a minimum hot gas temperature of θ_E is required to raise the temperature of a sprinkler element to θ_{nom} may be verified by performing a plunge test at θ_E using an instrumented sprinkler. The thermal response of the operating element of a re-assembled fast response type mounted sprinkler when plunged into the tunnel operating 0.5°C above θ_E, for this sprinkler at 88°C, indicates that the element approaches a steady temperature of about 75°C, Figure 8. It should approach a steady value asymptotically but would theoretically require an infinite time to level out. The tunnel air temperature was reduced by 0.5°C after 360 s to the average effective operating temperature of 87.5°C measured for this sprinkler using the rate of rise test. The element temperature also fell 0.5°C thereby confirming it had reached equilibrium and attained a steady value of 74.5°C which is the fusion temperature recorded by thermocouples fixed to the elements of identical but functional sprinklers at operation. A detailed theoretical analysis of this data has been presented elsewhere[2,4,15].

Classification of Thermal Sensitivity

Typical "dry" rate of rise test results for three sprinklers provisionally regarded as being representative of slow, medium and fast response are shown, Figure 9. The thermal response characteristics derived using the rate of rise test method indicate that sprinkler operation may be defined for a range of heating conditions using a characteristic temperature, the effective operating temperature, and a mean value for time constant which is appropriate to that range of condi-

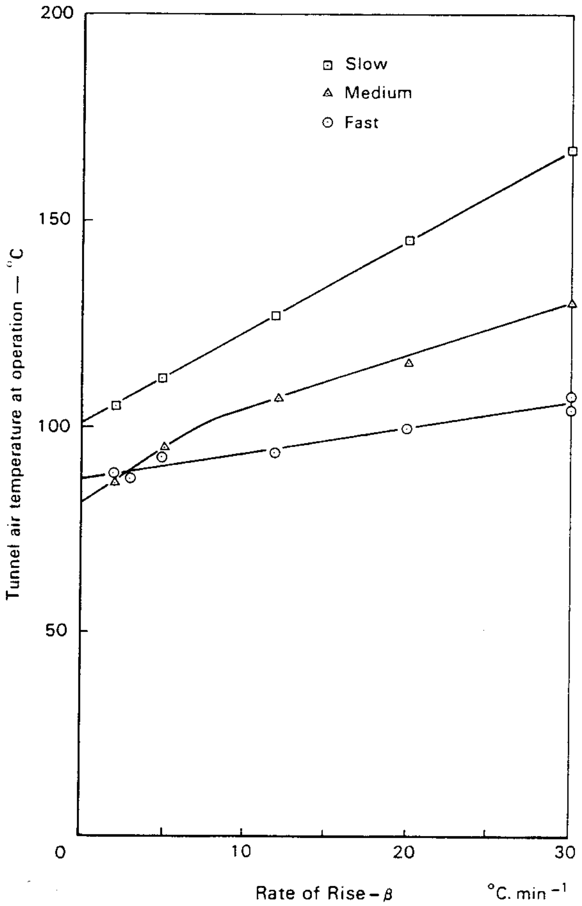

Figure 9. Rate of rise test results for slow, medium and fast response sprinklers.

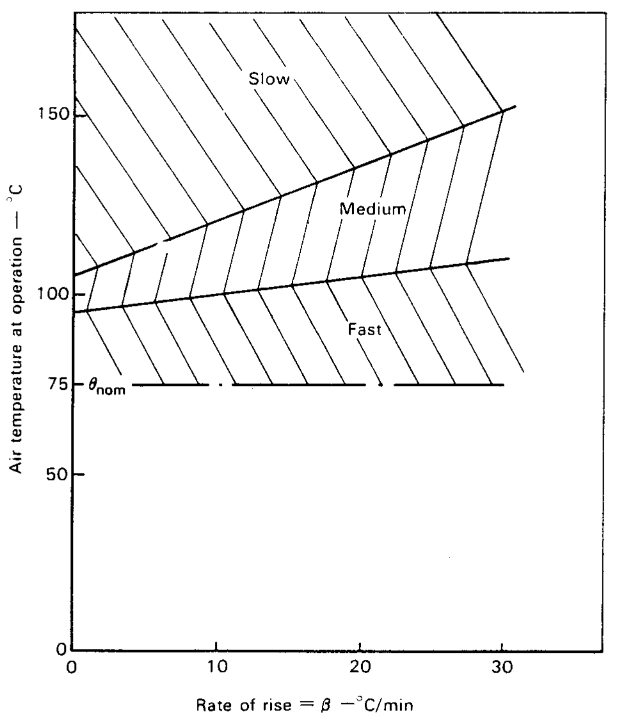

Figure 10. Suggested categories of sprinkler response.

tions. The "slow" and "fast" response sprinklers produce reasonably linear characteristics whereas a two stage characteristic was produced for the "medium" response sprinkler. The transition stage corresponding to the change in slope represents a change in the ratio between the rate of heat transfer to the element and thermal loss from the element of this sprinkler at rates of rise exceeding about 8°C/min. This result implies that conduction loss for this widely-used sprinkler is not a constant factor and may vary with the rate at which it is heated.

The thermal performance of these three sprinklers is suggested as a basis for classifying sprinklers into fast, medium or slow response categories[3] using the rate of rise test result format, Figure 10.

Factors Affecting Sprinkler Operation

The performance variations arising from changes in sprinkler orientation when tested "wet" or "dry" in the layer position (representing life safety use) or in the flue position (high rack use) with and without protective disc shields are shown for a fast response sprinkler in Figure 11. For slower response sprinklers, the corresponding differences may be much greater. It is therefore essential that sprinklers be tested "wet" and as realistically as possible. The non-linear results for this sprinkler also indicate that in some conditions, which are not at present predictable, the proportion of heat loss by conduction varies with heating rate.

Plunge Tests

The plunge test produces results which are particularly useful for monitoring sprinkler response for industrial purposes, e.g., for quality control and may also be used for performing repeat tests on samples within a batch to assess variance, i.e., the ratio of the standard deviation in time constant to the mean value measured for time constant, $\sigma / \bar{\tau}$.

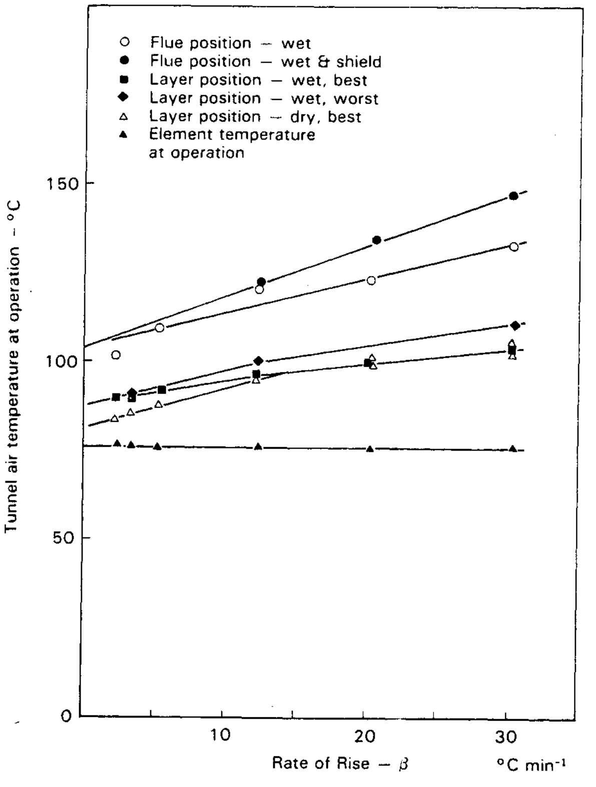

Figure 11. Rate of rise test results for fast response sprinkler.

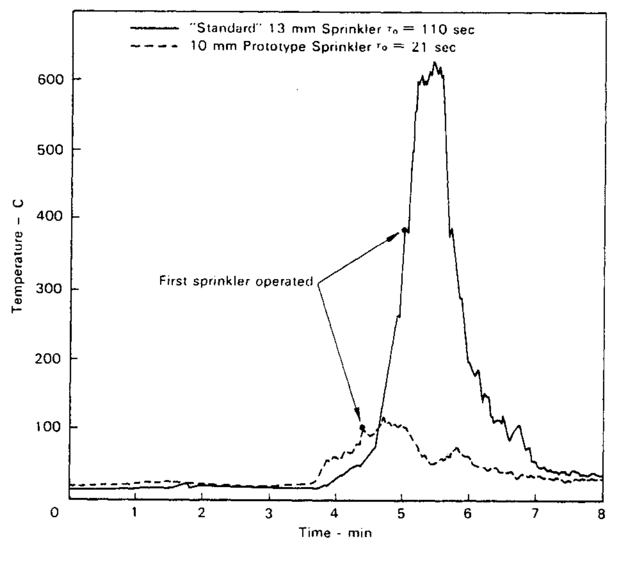

Figure 12. Comparison of gas temperature at first sprinkler location in living room.

DISCUSSION

Parameters

Velocity-independent parameters, such as the RTI and conductivity factor suggested by Heskestad and Bill[13], can be readily calculated from τ and θ_E derived from rate of rise tests[14]. In general, we will not expect these values to agree with those calculated directly from modified plunge tests. The theoretical descriptions used in each case, though equivalent, are inevitably approximations to reality. As a result, the parameters derived are test-method dependent. For reliable predictions of sprinkler response, the test method must therefore be chosen to represent realistic practical conditions.

Life Safety and High Rack Protection

Methods for measuring the thermal response characteristics of sprinklers are essential for reliably assessing the suitability of sprinklers for these applications. The sprinklers required for both purposes need to embody the latest techniques and technology available to the sprinkler industry for they have to operate within much reduced margins between the conflicting requirements of sensitivity, reliability and the virtual absence of false alarms, i.e., operation in non-fire conditions.

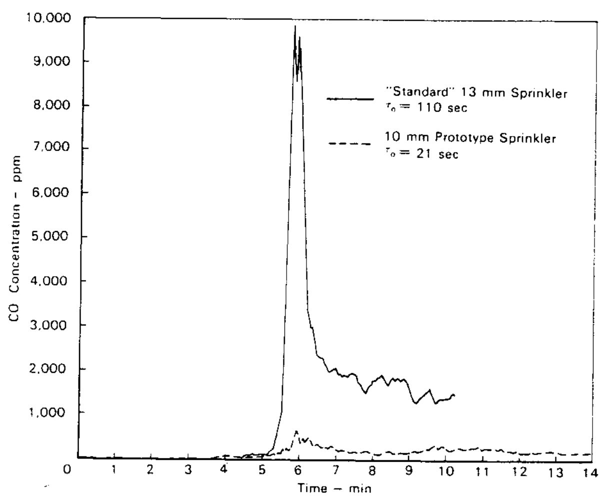

Figure 13. Comparison of CO concentration at eye level in living room.

Provided the hydraulic performance of a sprinkler is adequate, the thermal properties are the crucial features which determine whether or not the sprinkler gives protection. These properties should therefore be measured under conditions which are realistic for incipient fires.

The results of thermal tests on batches of sprinklers may be made significantly more consistent by the adoption of more severe test conditions, i.e., higher gas temperatures and higher gas velocities. This practice may fail by default to identify which sprinklers have reliability and/or consistency problems and which may fail to operate satisfactorily in the marginal fire conditions produced in the earliest stages of fire development when these sprinklers are required to operate. Such sprinklers may behave differently in rate of rise and plunge test conditions. The most unfavourable conditions for sprinkler operation occur when fire growth is slow and the element loses heat to its attachments and surroundings. The heating rates normally associated with the occupancies presented in *Applications for Fast Response Sprinklers* subjectively range from slow to fast. These conditions are mainly covered in the rate of rise test process and fully covered when this is supplemented by an additional plunge test to confirm correct operation when heated rapidly.

CONCLUSIONS.

1. The operational performance of sprinklers may be specified for comparison or approval use in terms of two thermal response characteristics, the effective operating temperature θ_E and the sprinkler time constant, τ. These two properties are measured using the rate of rise test and define the hot gas temperatures and exposure times required for operation for a range of heating conditions.

2. Variations in test methods and performance criteria will be required for different applications. Appropriate criteria are needed for sprinklers tested in the layer position for life safety use or in the flue position for high

rack protection. Approval bodies may require sprinklers to be tested in the least favourable orientation for life safety use. Sprinklers should be tested 'wet' unless specifically required for use in 'dry' systems.

3. The proportion of heat loss by conduction, from a sprinkler element may vary with the rate of heating. A range of ramp tests is needed to quantify this.

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