Principles for Fire Detection

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Abstract

A fundamental approach has been undertaken to provide principles for fire detection. Basic relationships have been developed for heat and chemical compound detectors and applied to duct and enclosure environments.

Introduction

Reliable fire detection is an essential aspect of fire protection in residential and industrial applications, both for the safe evacuation of people and for fire control or extinguishment. Fire detection is achieved by using various types of detectors: (1) heat detectors (e.g., fixed-temperature, rate-of-rise sensors); (2) chemical compound–smoke detectors (e.g., ionization, photoelectric sensors and gas detectors such as CO or CO_2 sensors); (3) flame detectors (e.g., ultraviolet and/or infrared sensors), etc. For effective detection of a fire, the most important parameter to evaluate is the total time associated with:

1. the occurrence of a specified hazard to people and buildings created by the fire, t_H;
2. the transit time of the fire product(s) to the detector location, t_t;
3. the fire growth time to reach a detectable level of fire product(s) at the detector location, t_f;
4. the detector response time once t_f has occurred, t_D; and
5 the "effective" response time once the fire has been detected, t_E. The relationship between these times can be expressed as:

$$t_r = t_H - (t_t + t_f + t_D + t_E) \tag{1}$$

where t_r = residual time, which must be greater than or equal to zero.

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Key Words: detection; response times; enclosures; heat detectors; chemical compound detectors.

In order to define detector performance for various types and locations of fires, a fundamental approach has been taken to provide generalized relationships for detection of fires in ducts and enclosures. Previous results have been applied to accurately determine t_t[1,2] and t_D has been quantified for a variety of detectors.[3] However, t_H, t_f, and t_E are more difficult to quantify.

t_H depends on the defined hazard, which is a function of the material properties and configuration. For example, previous work[1] has defined the propagation hazard for timber sets in mines relative to a heat flow parameter and a critical heat flux. When this parameter is greater than or equal to a given value, a fire will propagate. However, in this example, the "smoke" hazard might be defined as either more important for human escape or occurring more quickly than the propagation hazard. Thus, the time to the smoke hazard would be used for t_H. Table 1 gives some examples of tentative critical values for human escape. These critical values, therefore, could be used to define the level of the hazard. The characteristics of the material(s), the fire configuration, and the growth rate must be specified as well to determine the time to this level, t_H. In addition, when coupled with the response characteristics of a given fire detector, these quantities define t_f.

Table 1. Tentative critical values for human escape from fires for tolerable short-term exposure to fire products.*

Compound	Values for Human Escape (ppm)**
HCN	30–100
HCl	50–1,000
Benzene	1,500–4,000
$NO + NO_2$	100
SO_2	150
Cl_2	50
$COCl_3$	12.5
NH_3	2,500
CO	1,500–4,000
CO_2	40,000–80,000
O_2	60,000–100,000
Temperature (°C)	140
Smoke (OD)	0.22 m^{-1}

*Times ranging from 1 to 30 min.
**Data from References 4–7.

The effective response time, t_E, can be more difficult to assess than t_H or t_f; t_E depends on the individual duct or enclosure configuration, the location of the fire, and primarily on the method of response to the fire, such as automatic or manual fire fighting, ventilation control (e.g., fire doors), or simply evacuation. Thus, t_E could vary from the order of seconds, as in the case of automatic sprinklers, to the order of hours, as in the case of the evacuation of deep mines.

Basic Relationships

The following basic relationships were developed for the various times given in Equation 1.

Hazard Time (t_H)

For the duct configuration with the hazard specified in terms of ignition/propagation of the duct lining material,[1]

$$t_H = \left[\frac{(\rho_0 c_0 T_0 v_0 A_f)}{\alpha}\right] \mathrm{HFP}^{1/p} \tag{2}$$

where HFP, defined as the heat flow parameter,[1] is equal to

$$\dot{Q}_A / \rho_0 c_0 T_0 v_0 A_f$$

with

$\dot{Q}_A$ = actual heat release rate from the fire (kW);
ρ_0 = ambient gas density (kg/m^3);
c_0 = specific heat (kJ/kg K);
T_0 = temperature (K);
v_0 = average velocity (m/s);
A_f = cross-sectional area of the duct (m^2);
α = fire intensity parameter (kW/s^p); and
p = power law fire exponent.

If wall ignition is assumed at the fire source, than Equation 2 reduces to:

$$t_H = \left[\left(\frac{\dot{q}_{cr}''}{\sigma}\right)^{1/4} \frac{\rho_0 c_0 v_0 A_f}{\alpha}\right]^{1/p} \tag{3}$$

where $\dot{q}_{cr}''$ = critical heat flux for ignition of the wall material (kW/m^2); and σ = Stefan-Boltzmann constant (kW/K^{4}m^2). Table 2 gives examples of experimental values of $\dot{q}_{cr}''$ and HFP at the fire source with α (for p = 2) for wood and coal fires.[3]

Table 2. Parameters for coal and wood wall fires.

	Coal	Wood
$\dot{q}_{cr}''$ (kW/m^2)	20	10
HFP	1.6	1.2
α (kW/s^2)	1×10^{-4}	1×10^{-3}

Enclosure fire test data[2,8] and previously developed modeling relationships[9,10] were incorporated into a heat flux parameter. The resulting scaled heat flux is $\dot{q}''H^2/\dot{Q}_A$, where H = enclosure ceiling height (m) and H^2 is the scaling factor. For the enclosure configuration with the hazard specified as remote ignition of an object, a hazard time can then be defined as:

$$t_H = \left[\frac{4.0\,\dot{q}''_{cr}}{\dot{Q}_A} F \left(\frac{H}{h} \right) \right]^{1.1} \tau \tag{4}$$

where

F = enclosure floor area (m^2);

h = height of interest (m); and

τ = empirically determined time constant of the fire(s), defined as the time required to reach 63.2 percent of the steady-state heat release rate.

(Examples are given in Table 3 for various liquid pool fires.) Equation 4 has the restrictions that:

1. the maximum heat flux $\leq 0.34\,\dot{Q}_A / H(F)^{1/2}$
2. $0.5 \leq H(F)^{1/2} \leq 1.0$; and
3. $\dot{V}^{5/2} \leq 0.02$, where $\dot{V}$ = forced ventilation rate in the enclosure (m^3/s).

Table 3. Heat release rates and time constants for various liquid fuels.

Type of Fuel	Heat Release Rate $\dot{Q}_A''$ (kW/m²)	Time Constant τ(s)*
Methanol	380	$51D^{-1/2}$
Heptane	2700	$79D^{-1/2}$
#2 Fuel Oil	1400	$83D^{-1/2}$
Pennzoil	960	$96D^{-1/2}$

*D = pool diameter (m)

Transient Time (t_t)

For the duct configuration, the transit time is simply the horizontal displacement time;[1] i.e.,

$$t_t = l/v_0 \tag{5}$$

where l = distance downstream of the fire source (m).

Previous work[9] has shown that t_t, the time after ignition required for the smoke front from a fire source to reach various points under a flat

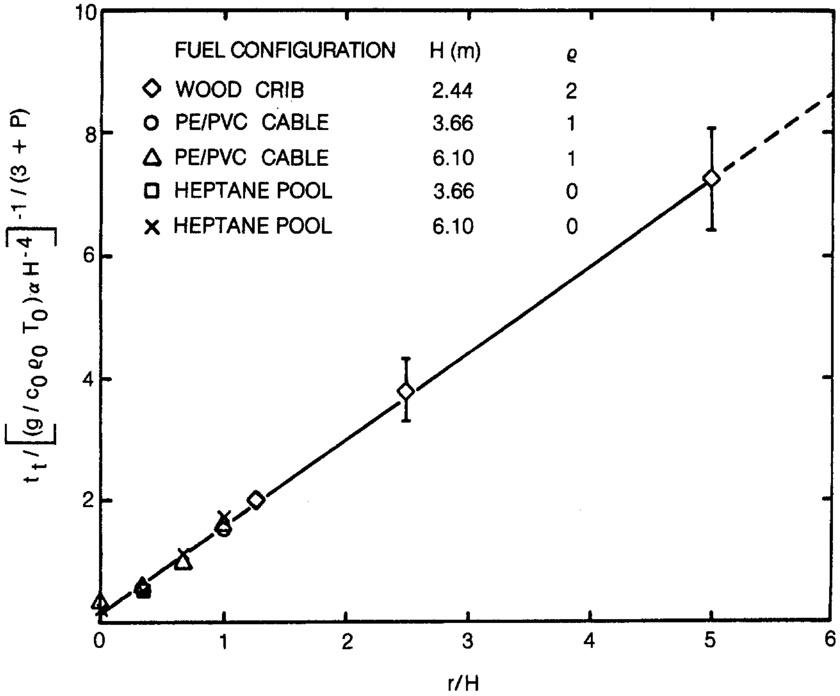

Figure 1. Scaled smoke transit time versus nondimensional radius from fire axis.

ceiling, can be represented by a scaled smoke transient time. This time, given in the following expression for power-law fires, can only be a function of the nondimensional location of the observation point:

$$t_t / \{(g/c_0\, \rho_0 T_0)^{-1/(3+p)}\, \alpha^{-1/(3+p)}\, H^{4/(3+p)}\} = f\ (r/H) \qquad (6)$$

For the enclosure configuration (from the data given in Figure 1),

$$t_{t,s} = 1.4\, r/H + 0.2$$

where $t_{t,s}$ = scaled transit time,[9]

$$[t_t/(g\ /c_0\rho_0 T_0)\,\alpha H^{-4}]^{-1/(3+p)}$$

with r = radial distance from the fire axis to the detector ceiling location (m).

Fire Growth Time (t_f)

For a given fire scenario within the duct, the fire growth time is dependent on two factors: the detector type and stratification effects. For example, from Equations 7–9 in Newman and Tewarson,[1] an expression can be obtained for t_f for a heat detector as a function of the average gas temperature in the duct, ΔT_{avg}, i.e.,

$$t_f = \left\{ \frac{(1+k_l)\rho_0 c_0 v_0 A_f \Delta T_{avg} + A_w \sigma [(\Delta T_{avg} + T_0)^4 - T_0^4]}{\alpha} \right\}^{1/p} + l_D / v_0 \tag{7}$$

where k_l is the convective loss coefficient at l_D (defined in Newman and Tewarson[1]); and A_w is the wall surface area of the duct (m^2).

Equation 6 of Newman[12] can be employed to assess the local temperature rise, ΔT_{avg} and v_{avg}:

$$\Delta T_h = 1.8 \left[\frac{gH}{T_{avg} v_{avg}^2} \right]^{0.23} \Delta T_{avg}^{1.23} \tag{8}$$

where

g = acceleration due to gravity;

H = ceiling height of passageway (m); and

$v_{avg} = T_{avg} (v_0 / T_0)$.

With the assumptions that $v_{avg} \cong v_0$ and T_h = 330 K (alarm threshold for 135°F heat detector) and solving for ΔT_{avg} in Equation 8,

$$\Delta T_{avg} = \left[\frac{330 - T_0}{1.8} \right]^{0.81} \left[\frac{T_0 v_0}{gH} \right]^{0.19} \tag{9}$$

Equation 9 combined with Equation 7 can now be employed to asses t_f for heat detectors.

For chemical-compound detectors, Newman[12] demonstrates that the mass concentration, C_i, of any chemical compound, i, follows the local gas temperature rise; i.e.,

$$\frac{C_{i,h}}{C_{i,avg}} = \frac{\Delta T_h}{\Delta T_{avg}} \tag{10}$$

where $C_{i,avg}$ = average mass concentration of i; and $C_{i,h}$ = concentration of i at detector height, h. If stratification is considered negligible (weakly buoyant fire or large values of l_D), then the following simplified expression for t_f can be developed:

$$t_f = \left[\frac{\rho_0 v_0 A_f}{1000\,\alpha} \left(\frac{\Delta C_{i,f}}{Y_i \,/\, H_A} \right) \right]^{1/p} \quad \text{for a gas detector} \qquad (11a)$$

or

$$t_f = \left[\frac{v_0 A_f}{\alpha} \left(\frac{\mathrm{OD}_f}{\xi / H_A} \right) \right]^{1/p} \quad \text{for a smoke detector} \qquad (11b)$$

where

$\Delta C_{i,f}$ = alarm level concentration of gas species i (ppm);
Y_i = yield of gas species i (g/g);
H_A = actual heat of combustion of fire source (kJ/g);
OD_f = alarm level value of optical density (m^{-1}); and
ξ = mass attenuation coefficient (m^2/g).

However, if stratification of i is significant, the temperature stratification must first be determined and then t_f calculated for the specific detector type. For enclosures, the relationship for t_f is currently being developed.

Detection Time (t_D)

For a heat-type detector, the response is characterized by the response time index,[13] or RTI; i.e.,

$$\mathrm{RTI} = \tau v^{1/2} \qquad (12)$$

where τ = time constant of the sensing element(s).

For a gas detector, the time response is given as:[14]

$$\frac{dC_s}{dt} = \frac{1}{\tau} [C_0 \, (t - t_l) - C_s \,] (t) \qquad (13)$$

where

C_s = instantaneous gas concentration as measured by the sensor at time t (ppm);
C_0 = reference gas concentration at time $t - t_l$ (ppm); and
t_l = sensor lag time (s).

For an ionization smoke detector, the detector response can be expressed by:[14]

$$\ln \, (I_0 \,/\, \Delta I) \cong a f_v = \frac{7.0\,\mathrm{a}}{\lambda (\mathrm{OD}_\lambda)} \qquad (14)$$

where

$I_0/\Delta I$ = ratio of initial current to the change in current;
a = the detector/material sensitivity given in Table 4;
f_v = the particulate volume fraction; and
OD_λ = the optical density (log base e in m^{-1}) at a specific wavelength, λ,of light absorption.

Details of the relationship between OD_λ and f_v are given elsewhere.[15]

Table 4. Ionization smoke detector response.

Fuel	a (10^{-8} m^{-1})
Douglas Fir	0.27
Heptane	0.56
Coal	0.92
Polyvinyl Chloride (PVC)	0.98
Styrene-butadiene Rubber (SBR)	1.9
Polystyrene (PS)	2.2

Application

To conveniently handle the t_r and t_E terms in Equation 1, the concept of a safety parameter has been employed, such that

$$(t_r + t_E) = X t_H \tag{15}$$

where the safety parameter, X, has values between 0 and 1; i.e., the larger the value of X, the more time available for response to the fire after detection. Combining Equations 1 and 15 yields:

$$(1-X)t_H = t_t + t_f + t_D \tag{16}$$

Table 5. "Typical" conditions in a conveyor belt haulageway.[3]

Ambient temperature, T_0	= 291 K (65°F)
Ventilation rate, $\dot{V}$	= 1.9 $\mathrm{m^3/s}$ (4000 cfm)
Ceiling height, H	= 1.5 m (5 ft)
Passageway width, W	= 4.9 m (16 ft)
Cross-sectional area, A_f	= $H \times W$ = 7.4 $\mathrm{m^2}$ (80 $\mathrm{ft^2}$)
Ambient velocity, v_0	= $\dot{V}A_f$ = 0.25 m/s (50 fpm)

Table 6. Detector spacing for a "typical" coal mine (X = 0.5).

Detector	Type	Alarm/Alert Level	τ (s)	t_t (s)	t_D (s)	l (m)
"Ideal"	heat	Δ39°C	0	0	0	75
Thermotech	heat	Δ35°C	24	—	24	75
MSA	heat	Δ39°C	106	—	106	70
Pyott-Boone	heat	Δ37°C	764	—	764	20
Ecolyzer	CO	Δ10 ppm/Δ5 ppm*	23	16	39	340
MSA	CO	Δ10 ppm/Δ5 ppm*	29	14	43	340
Spanair	CO_2	Δ200 ppm/Δ100 ppm*	672	88	760	170
Becon	Smoke	0.05 $\mathrm{m^{-1}}$/0.025 $\mathrm{m^{-1}}$*	~0	~0	~0	400

* Suggested levels

Table 7. Grouped cable tray fires.

Time (s) [spacing (ft × ft)]	Test 2 (X)	Test 3 (X)
t_B	1700	1000
Detector alarm (10 × 10)	24 (0.99)	25 (0.98)
Detector alarm (20 × 20)	36 (0.98)	39 (0.96)
Detector alarm (30 × 30)	55 (0.97)	48 (0.95)
Sprinkler actuation (10 × 10)	374 (0.78)	290 (0.71)

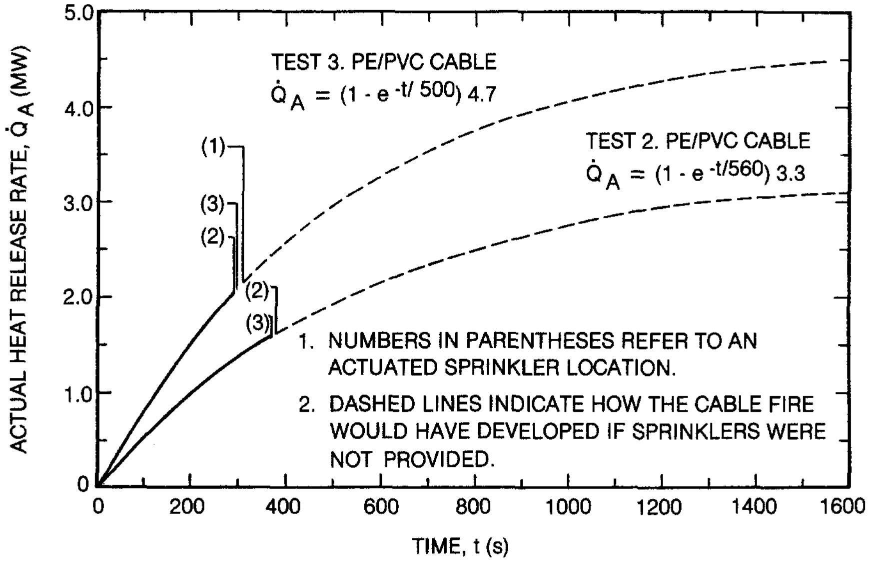

Figure 2. Heat release rates for cable tray fire tests.

Equation 16 has been evaluated for the two fire environments previously identified. For the duct configuration, Equation 16 combined with Equations 2, 5, and 11 results in the following equation:

$$(1-X)\left[\frac{\rho_0 v_0 A_f}{\alpha}\right]^{1/p}\left[\mathrm{HFP}\,(c_0 T_0)-\frac{\Delta C_{i,f}}{1000\,(Y_i/H_A)}\right]^{1/p} = l/v_0 + t_D \qquad (17)$$

where the required inputs are: geometry (A_f); ambient conditions (ρ_0, c_0, T_0, v_0); type of fire (α, HFP, Y_i, H_A); detector (t_D, $\Delta C_{i,f}$); and safety parameter (X). The output is the detector spacing (l). For example, for a conveyor belt haulageway in a "typical" coal mine (defined in Table 5 from Newman and Khan[3]), detection times are given in Table 6 for various detector types using a value for the safety parameter of 0.5. As shown in the table, depending on the specific detector, the spacing can range between 20 and 400 m for the same design level.

For the ventilated enclosure, data from Newman[8] for two large-scale cable tray fire tests were evaluated. The actual heat release rates versus time are shown in Figure 2. For the two tests, Table 7 gives values of t_H (calculated from Equation 4), detection times on 10 × 10, 20 × 20 and 30 × 30 ft spacings, and sprinkler actuation times for the 10 × 10 ft spacing. Values of X, given parenthetically for each detector/sprinkler spacing in the table, illustrate that smoke detectors provide a minimum safety parameter of 0.95, while sprinklers provide a value of X greater than 0.7. It should be noted that, in this example, the sprinkler is treated as a fixed-temperature heat detector coupled with a wet-pipe system. Thus, while the smoke detectors provide considerably more time for response after detection, the "effective" response could be quite slow if the detector serves only as annunciator (as opposed to an extinguishing system actuator). Clearly, the actual response following detection has a major impact on the level of safety provided by a given fire detection/protection system.

Summary

1. A fundamental time relationship for detection has been defined based upon the hazard, transit, fire growth, detection, and "effective" response times.
2. Basic relationships have been established for the response of heat and chemical compound detectors in duct and enclosure fire environments.
3. The developed relationships have been applied to a "typical" coal mine and a cable-tray installation.

Nomenclature

a	detector/material sensitivity factor (m^{-1})
A	area of duct (m^2)
c	specific heat (kJ/kg K)
C	concentration rise of chemical compound (ppm or g/g)
F	floor area (m^2)
f_v	particulate volume fraction (m^3/m^3)
g	acceleration of gravity (m/s^2)
h	height of interest (m)
H	ceiling height (m)
H_A	actual heat of combustion (kJ/g)
HFP	heat flow parameter
I	detector current
ΔI	change in detector current
l	horizontal length (m)

OD	optical density base e (m^{-1})
p	power law exponent
$\dot{Q}_A$	actual heat release rate (kW)
$\dot{q}''$	heat flux (kW/m^2)
RTI	response time index (m·s)$^{1/2}$
t	time(s)
T	temperature (K)
ΔT	temperature rise above ambient (K)
v	gas velocity (m/s)
$\dot{V}$	ventilation rate (m^3/s)
X	safety parameter
Y	mass yield of chemical compound (g/g)

Greek

α	proportionality constant of power law fire (kW/s^p)
λ	wavelength of light (μ)
ξ	mass attenuation coefficient (m^2/g)
ρ	gas density (kg/m^3)
σ	Stefan-Boltzmann constant (56.703 nW/m^2 K^4)
τ	time constant (s)

Subscripts

avg	average
cr	critical
D	detection
E	effective
f	fire or flow
h	height of interest
H	hazard
i	individual chemical compound
l	horizontal distance
0	ambient air or reference
r	residual
s	sensor or scaled
t	transit
w	walls
λ	wavelength of light

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Acknowledgements: The financial support of the United States Bureau of Mines, Pittsburgh, Pennsylvania, under Contract No. H0113017 and technical direction of Dr. A. F. Cohen, is deeply appreciated.