Rearrange for T—

$$T = \frac{V_a G}{F} \ln\left(\frac{G}{G - \left(L/_K\right)}\right)$$

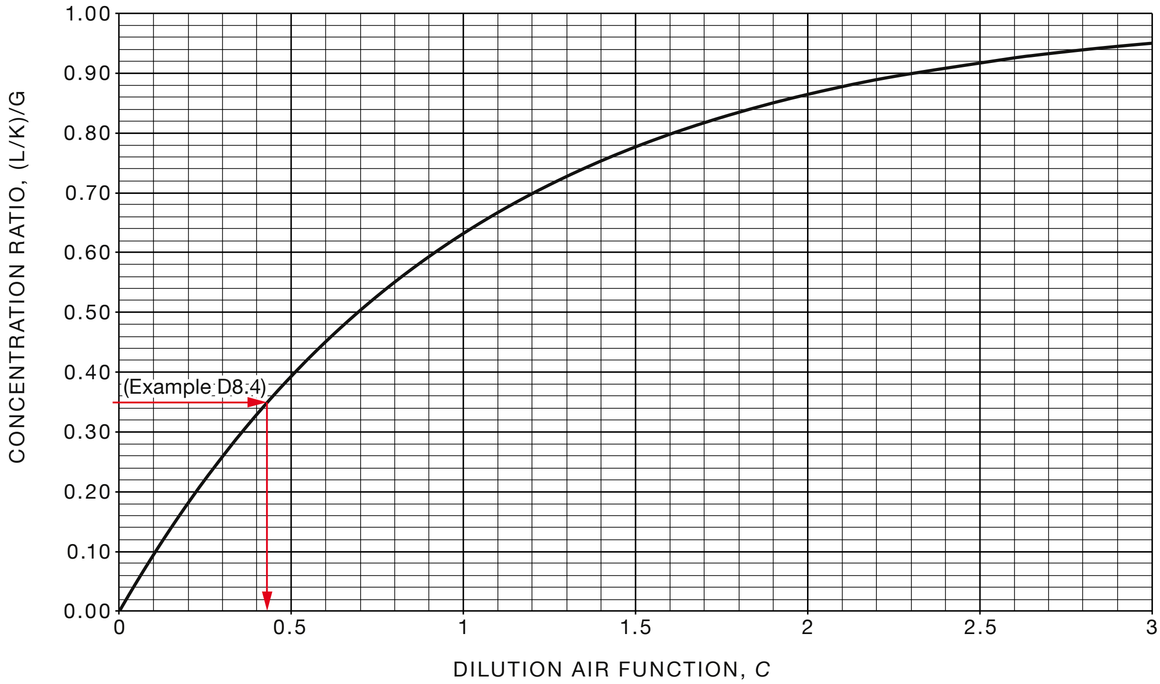
$$T = \frac{V_a C}{M}$$

where

$$M = \frac{F}{G}$$

$$C = \ln\left(\frac{G}{G - \left(L/_K\right)}\right)$$

and may be read from Figure D1 in which C is plotted against $(L/K)/(G)$ or L/GK which is the ratio of the maximum permissible concentration (L/K) to the actual concentration (G).



NOTE: $C = \ln\left(\frac{G}{G - \left(L/_K\right)}\right)$

FIGURE D1 DILUTION AIR FUNCTION C

D7 DERIVATION OF FORMULA, CASE C

As (L/K) approaches G, C approaches infinity and hence T approaches infinity. That is if (L/K) is greater than or equal to G then the mixture can never exceed the lower flammability limit and T is infinite.

$$\lim_{L/K \to G} \frac{V_c}{M} \ln\left(\frac{G}{G - \left(L/K\right)}\right) \to \infty$$

Thus if $(L/K) \geq G$, then $C \to \infty$ and $T \to \infty$.

D8 EXAMPLES

D8.1 General

This Paragraph D8 has been provided as a guide to the reader on the calculation of critical time for Cases A, B and C, it is to be considered informative.

D8.2 Case A—using Equation D1

Natural Gas

$$T = \frac{P_p V_c R}{P_m F} \qquad \text{. . . (D1)}$$

P_p = 700 kPa = 700 000 Pa (Ref. E4.2)

P_m = 700 kPa = 700 000 Pa (Ref. Table G1)

$R = 0.095\ \mathrm{m^3/m^3}$ (Ref. Table G1)

$V_c = 3\ \mathrm{m^3}$ (from appliance design)

Appliance rating = 150 MJ/h (burner spec)

$H = 39\ \mathrm{MJ/m^3}$ (from fuel spec)

$F = 150/39/3600 = 0.001\ \mathrm{m^3/s}$

$$T = \frac{700\,000 \times 3 \times 0.095}{700\,000 \times 0.001}$$

= 267 seconds (4 m 27 s)

Distillate

$$T = \frac{P_p V_c R}{P_m F} \qquad \text{. . . (D1)}$$

P_p = 700 kPa = 700 000 Pa (Ref. E4.2)

P_m = 900 kPa = 900 000 Pa (Ref. Table G1)

$R = 0.087\ \mathrm{kg/m^3}$ (Ref. Table G1)

$V_c = 3\ \mathrm{m^3}$ (from appliance design)

Appliance rating = 3.3 L/h (burner spec)

= 149 MJ/h

H = 45.3 MJ/kg (fuel spec)

= 45.3 MJ/L (fuel spec)

$F = 149/45.3/3600 = 0.0009$ kg/s

$$T = \frac{700\,000 \times 3 \times 0.080}{900\,000 \times 0.0009}$$

= 226 seconds (3 m 46 s)

D8.3 Case A—using Equation D2

Natural Gas

$$T = \frac{5P_p V_c}{I} \quad \ldots (D2)$$

P_p = 700 kPa = 700 000 Pa (Ref. E4.2)

V_c = 3 m^3 (from appliance design)

Appliance rating = 150 MJ/h (burner spec)

$$I = \frac{150\,000\,000}{3600}$$

= 41 667 J/s

$$T = \frac{5 \times 700\,000 \times 3}{41\,667}$$

= 252 seconds (4 m 12 s)

Distillate

$$T = \frac{5P_p V_c}{I} \quad \ldots (D2)$$

P_p = 700 kPa = 700 000 Pa (Ref. E4.2)

V_c = 3 m^3 (from appliance design)

Appliance rating = 149 MJ/h (burner spec)

$$I = \frac{149\,000\,000}{3600}$$

= 41 389 J/s

$$T = \frac{5 \times 700\,000 \times 3}{41\,389}$$

= 254 seconds (4 m 14 s)

NOTE: The assumption that RH = 4 MJ/m^3 is not valid for liquid or solid fuels. This method should not be used with these fuels.

D8.4 Case B—Calculation method

Natural Gas

$$T = \frac{V_a G}{F} \ln\left(\frac{G}{G - L/K}\right) \quad \ldots (D9)$$

L = 0.05 m^3/m^3 (Ref. Table G1)

K = 2 (Ref. D2)

V_c = 3 m^3 (from appliance design)

H = 39 MJ/m^3 (from fuel spec)

Appliance rating = 150 MJ/h (burner spec)

F = 150/39/3600 = 0.001 m^3/s

Air rate = 47 m^3/h (burner spec)

= 47/3600 = 0.013 m^3/s

$$G = \frac{F}{F + \text{Air rate}}$$

$$= \frac{0.001}{0.001 + 0.013}$$

= 0.071

$$T = \frac{3 \times 0.071}{0.001} \ln\left(\frac{0.071}{0.071 - 0.05/2}\right)$$

= 92.4 seconds (1 m 32 s)

Distillate

$$T = \frac{V_a G}{F} \ln\left(\frac{G}{G - L/K}\right) \quad \ldots (D9)$$

L = 0.048 kg/m^3 (Ref. Table G1)

K = 4 (Ref. D2)

V_c = 3 m^3 (from appliance design)

Appliance rating = 3.3 L/h (burner spec)

= 149 MJ/h

H = 45.3 MJ/kg (fuel spec)

= 40.2 MJ/L (fuel spec)

F = 149/45.3/3 600 = 0.0009 kg/s

$$G = \frac{F}{F + \text{Air rate}}$$

$$= \frac{0.0009}{0.0009 + 0.013}$$

= 0.065

$$T = \frac{3 \times 0.065}{0.0009} \ln\left(\frac{0.065}{0.065 - 0.0480/4}\right)$$

T = 44.2 seconds (1 m 20 s)

D8.5 Case B—Using Figure D1

Natural Gas

$$T = \frac{V_a C}{M} \quad \ldots \text{(D6)}$$

$L = 0.05\ m^3/m^3$ (Ref. Table G1)

$K = 2$ (Ref. D2)

$V_c = 3\ m^3$ (from appliance design)

$H = 39\ MJ/m^3$ (from fuel spec)

Appliance rating = 150 MJ/h (burner spec)

$F = 150/39/3600 = 0.001\ m^3/s$

Air rate = 47 m^3/h (burner spec)

= 47/3600 = 0.013 m^3/s

$$G = \frac{F}{F + \text{Air rate}}$$

$$= \frac{0.001}{0.001 + 0.013}$$

$$= 0.071$$

$$M = \frac{F}{G}$$

$$= \frac{0.001}{0.071}$$

$$= 0.014\ m^3/s$$

$$\text{Concentration Factor} = \frac{L}{GK}$$

$$= \frac{0.05}{0.071 \times 2}$$

$$= 0.35$$

Find C from Figure D1

$C = 0.43$

$$T = \frac{3 \times 0.43}{0.014}$$

= 92.1 seconds (1 m 32 s)

Distillate

$$T = \frac{V_a C}{M} \quad \ldots \text{(D6)}$$

$L = 0.048\ kg/m^3$ (Ref. Table G1)

$K = 4$ (Ref. D2)

$V_c = 3\ m^3$ (from appliance design)

$H = 45.3$ MJ/kg (fuel spec)

= 40.2 MJ/L (fuel spec)

Appliance rating = 3.3 L/h (burner spec)

= 149 MJ/h

$F = 149/45.3/3600 = 0.0009$ kg/s

Air rate = 47 m^3/h (burner spec)

= 47/3600 = 0.013 m^3/s

$$G = \frac{F}{F + \text{Air rate}}$$

$$= \frac{0.0009}{0.0009 + 0.013}$$

$$= 0.065$$

$$M = \frac{F}{G}$$

$$= \frac{0.0009}{0.065}$$

$$= 0.014\ m^3/s$$

$$\text{Concentration Factor} = \frac{L}{GK}$$

$$= \frac{0.080}{0.065 \times 4}$$

$$= 0.185$$

Find C from Figure D1

$C = 0.205$

$$T = \frac{3 \times 0.185}{0.014}$$

$$= 39.6 \text{ seconds}$$

D8.6 Case C

Natural Gas

$$\frac{L}{K} \geq GT = \infty$$

L = 0.05 m^3/m^3 (Ref. Table G1)

K = 2 (Ref. D2)

H = 39 MJ/m^3 (from fuel spec)

Appliance rating = 150 MJ/h (burner spec)

F = 150/39/3600 = 0.001 m^3/s

Primary air rate = 47 m^3/h (burner spec)

= 47/3600 = 0.013 m^3/s

Secondary air rate = 150 m^3/h (app spec)

= 150/3600 = 0.042 m^3/s

$$G = \frac{F}{F + \text{Primary air} + \text{Secondary air}}$$

$$= \frac{0.001}{0.001 + 0.013 + 0.042}$$

= 0.018

$$\frac{L}{K} = \frac{0.050}{2} = 0.025$$

$L/K \geq G$ (0.025 ≥ 0.018) hence T is infinite

Distillate

$$\frac{L}{K} \geq G \rightarrow T = \infty$$

L = 0.087 kg/m^3 (Ref. Table G1)

K = 4 (Ref. D2)

H = 45.3 MJ/kg (fuel spec)

= 40.2 MJ/L (fuel spec)

Appliance rating = 3.3 L/h (burner spec)

= 149 MJ/h

F = 149/45.3/3600 = 0.0009 kg/s

Primary air rate = 47 m^3/h (burner spec)

= 47/3600 = 0.013 m^3/s

Secondary air rate = 150 m^3/h (app spec)

= 150/3600 = 0.042 m^3/s

$$G = \frac{F}{F + \text{Primary air} + \text{Secondary air}}$$

$$= \frac{0.0009}{0.0009 + 0.013 + 0.042}$$

= 0.016

$$\frac{L}{K} = \frac{0.087}{4} = 0.022$$

$L/K \geq G$ (0.02 ≥ 0.016) hence T is infinite

APPENDIX E
RELIEF OF EXPLOSIONS
(Informative)

E1 INTRODUCTION

Since the 1985 edition of this Standard much work has been done to improve the knowledge of explosions and the prevailing mechanisms that take place during the event. Various standards have now evolved which provide expert guidance in the estimation of vent areas for the mitigation of damage due to uncontrolled explosive events in an appliance. These standards now cover in detail applications for gases and solvents in a vapour form as well as dusts.

This Appendix provides a simplified method that is still valid today and provides some measure of protection during an explosion with the proviso that the constraints indicated with the various methods are not exceeded. Where the constraints that apply to the case in point are outside the valid application of the methods outlined, NFPA 68 is the preferred standard that is to be adopted unless specific acceptance is provided by the technical regulator having jurisdiction.

NFPA 68 is to be used in cases where dusts and mixtures of gases and dusts are present in concentrations that form a combustible mixture.

Each appliance should be studied individually to assess the effects of internal partitions, changes of direction, obstruction by goods in process, internal or external obstructions of the discharge path, likely locations of ignition sources, and the like.

An explosion is essentially an occurrence of uncontrolled combustion in which a flame front propagates from the source of ignition, generating rapidly heated combustion gases. If these hot products are so enclosed as to inhibit free expansion, a pressure is developed, and it is this pressure which causes such damage as occurs.

The extent of damage is influenced by two factors, the peak explosion pressure and the rate of flame propagation, both of which are peculiar to the particular materials involved, but which nevertheless present certain general patterns.

The pressure developed in a normal deflagration type of explosion, as distinct from a detonation, does not vary greatly from one material to another, being generally of the order of 700 kPa under optimum fuel/air conditions, so it is usually safe to assume a value of 800 kPa if the precise figure for the material is not known or if a number of alternative materials are to be used. Exceptions are dusts, many of which can be unexpectedly explosive (see Appendix G, Table G2, or NFPA 68 for a more comprehensive list), and should therefore be checked individually. Maximum pressure usually occurs at a mixture slightly richer than stoichiometric ratio, but may be assumed to occur at stoichiometric ratio without significant error. Departures from this rule have been observed, but relate to dust clouds, and are thought to result from uneven particle distribution during experimental explosions.

A combustible material that has a high rate of flame propagation will reach its peak explosion pressure more rapidly than will a slower burning material, with two significant effects: first, less time is available for the explosion product gases to move through the vent orifice; and secondly, less time is available to accelerate the mass of the hatch or to burst the membrane. Therefore fast-burning materials characteristically generate slightly higher peak pressures before reliefs operate. An explosion in a fast-burning material such as manufactured gas will develop maximum pressure in about one-third of the time required for a slower burning material such as methane or acetone or any of the common solvents.

Flame propagation rates are given in Tables G4 and G5. Indications are that few common materials burn faster than 0.5 m/s, so a value of 1 m/s would be a safe assumption in the absence of specific figures. Gases that are rich in free hydrogen are a notable exception. For obvious reasons the volume of the enclosure will also affect the pressure/time relationship, the time to reach maximum pressure will take longer in a large enclosure than in a small one because of the time required for the flame-front to propagate.

Where a relief orifice is closed by a hatch or membrane, the curve of pressure rise will usually exhibit two peaks, the first caused by the need to build up sufficient pressure to burst the membrane or to overcome the inertia of the hatch, the second by the throttling effect of the vent orifice. Many design procedures are limited to determining the area of opening that controls the latter, and overlook the former. It is particularly easy to fail to consider the effect of inertia in the case of a hatch. If it is of considerable mass, the first pressure peak, which is inadvertent, may well exceed the second or design pressure peak, leading to damage to appliances that are apparently theoretically safe.

Work done in the UK on gas-fired ovens (Refs [2] and [3]) resulted in a formula that relates the ultimate explosion pressure to the burning velocity of the gas, to the ratio between vent area and cross-sectional area of the appliance, and to the mass of the closure. Work of others (Refs [6] and [11]) has confirmed the general validity of the area/area approach and an analysis (Ref. [13]) of a number of independent experiments indicated a hitherto unnoticed degree of consistency when the results were translated to this basis.

References [2] and [3] are therefore the basis for the method given in this Standard, with one important qualification, i.e. for rectilinear ovens the area of an explosion relief may be calculated on the basis of the smallest cross-section of the appliance. Experimental results tabulated in the reports justify this procedure. The authors of the report proceeded further than this conclusion, and recommended two alternative design procedures i.e. either proportion the vent area in relation to the side in which it is mounted, or else work on the basis of a cube of equivalent volume. Both procedures result in larger vents than the minimum necessary, and hence they increase safety margins, but these were considered to be so conservative in relation to the actual findings that it was impossible to justify their adoption in a standard of this nature.

References 5 and 6 are the basis for the method for longer appliances of small section and ducts. These methods are considered to have ample experimental backing, within the limits implicit in the parameters of the original experiments.

E2 OUTLINE OF DESIGN PROCEDURE

(a) Determine the maximum allowable pressure within the appliance in accordance with Paragraph E4.

(b) Determine the unrestricted area of open relief vent that will permit the heated gases produced by the explosion to escape without building up a pressure that exceeds the permissible pressure adopted in (a) above. Procedure is given in Paragraph E5.

(c) Design the closure of the relief vent so that its resistance to opening will not cause the allowable pressure to be exceeded. (See Paragraph E6.)

E3 SYMBOLS

The following symbols are used in the formulas given in this Appendix:

A = least cross-section area of the appliance, in square metres

D = mean hydraulic diameter, i.e. $4A$ divided by perimeter, in metres

K = A/R

L = length of appliance or duct, in metres (see Figure E1)

M = mass of vent closure, in kilograms

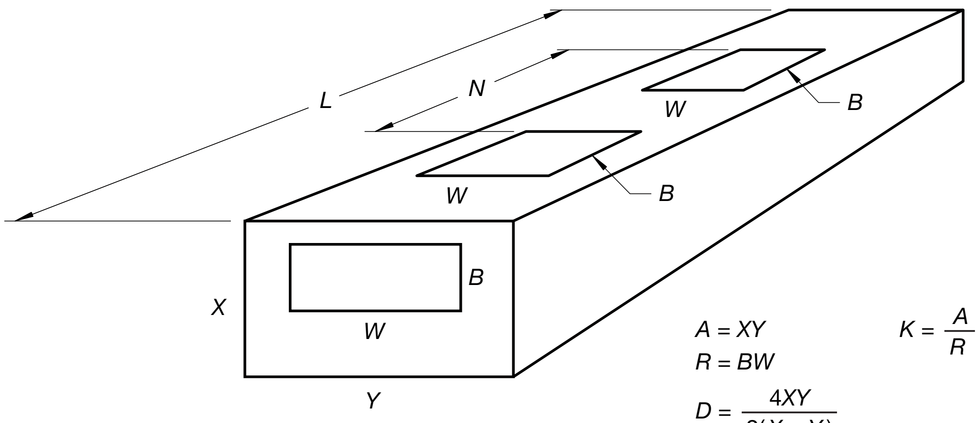
N = spacing of multiple vents in a long appliance, in metres

P = design pressure or maximum allowable pressure, in kilopascals

R = net effective area of relief vent opening, in square metres

S = flame speed propagation rate, in metres per second (see Table G7)

V = volume, in cubic metres



$A = XY$

$R = BW$

$D = \frac{4XY}{2(X+Y)}$

$K = \frac{A}{R} = \frac{XY}{BW}$

FIGURE E1 ILLUSTRATION OF SYMBOLS IN PARAGRAPH E3

E4 DETERMINATION OF MAXIMUM ALLOWABLE PRESSURE

E4.1 Objective

The procedures in this Appendix have as their objective the protection of personnel, and will not necessarily prevent some degree of physical damage to the appliance. If the avoidance of any damage is required, then it will be necessary to consider allowable pressures with this end specifically in view.

E4.2 Determination of strength

The maximum allowable internal pressure for an appliance should be calculated wherever possible using conventional engineering design methods as appropriate to the particular form of construction.

Where calculation is not possible, a value for allowable internal pressure should be estimated from available information, particularly from the recorded results of experiments.

While some appliances can withstand the maximum pressure developed in an explosion (600 kPa to 800 kPa), the great majority are comparatively weak and may suffer damage at pressures as low as 5 kPa to 10 kPa.

It is assumed for the purposes of this Standard that an internal pressure below 7 kPa is generally unlikely to endanger personnel, although it may damage the appliance.

NOTES:

1 Consideration should be given to options that will restrict the internal pressure to a maximum of the following values which have been selected from available experimental sources to serve as a guide when calculation is not possible:

(a) Small well-constructed double-skin box ovens up to 3 m^3 volume (Ref. [2] and [3]).. 15 kPa.

(b) Lightly constructed metal-cased ovens up to 3 m^3 volume (Refs [2] and [3]) .... 7 kPa.

(c) Ovens over 3 m^3 volume, any construction .... 7 kPa.

(d) Ducts of normal light sheet metal construction (Refs [2] and [3]) .... 7 kPa.

2 Data on brickwork are unreliable and inconsistent. The tests described in Refs [4] and [5] relate to brickwork of the type used in normal building construction and may not be relevant to furnace brickwork.

3 Additional test results from ductwork and enclosures, made from light gauge steel is available in Ref. [15].

E5 DETERMINATION OF RELIEF VENT AREA

The recommendations given below are drawn from experiments conducted by the various persons or organizations quoted in the references. The limitations within which the various experiments were conducted are noted, and these constitute the limits of confidence, beyond which there is no proof that the calculations remain valid.

For the determinations outside these limits of confidence, refer to NFPA 68.

(a) *Cubic or near cubic appliances*:

$$R = 8\left(\frac{AS}{P}\right)$$

Validated experimentally within the following limits:

(i) $L \leq 2.25$D

(ii) $P \leq 35$ kPa

(iii) $V \leq 100$ m3

Maximum explosion pressure ≤700 kPa.

(b) *Longer appliances (L exceeds 2.25D)* Divide the appliance into segments for which L does not exceed $2.25D$ and calculate for each segment a value for R, using (a) above. The areas may be aggregated and a single relief used only in very favourable circumstances, e.g. L is less than $3D$, the vent location is central and gas flow to it is good. Otherwise multiple vents are recommended.

(c) *Ducts* The following alternatives may be used within the specified limits of validity:

(i) $R = A$

Valid for a single vent where—

D <750 mm

$$L < \frac{0.8PD}{S} \text{ and} \leq 30D$$

$K = 1$

NOTE: Where L exceeds the limits specified above, divide into segments which qualify, and treat each segment as an individually vented appliance, applying the above.

(ii) Section 8 of NFPA 68.

(d) *Additional provisions for adverse circumstances* The areas calculated above are the minimum necessary to cater for comparatively unobstructed enclosures in which expanding gases can flow freely to outlets. The appliance design should now be examined for internal partitions, product loading patterns, direction changes, and any other factors relating to vent location (see Paragraph E7) which might adversely affect vent functioning. Larger vents, or additional vents in critical locations, may need to be provided to ensure reliable operation.

E6 DETERMINATION OF THE OPENING CHARACTERISTICS OF THE RELIEF VENT CLOSURE

E6.1 Introduction

As noted in Paragraph E1, when a relief orifice is closed by a hatch or membrane, it is most important that such a closure should offer the minimum possible resistance to opening, in order to limit the size of the primary pressure peak. The design of the vent closure should be such that the mass/area ratio does not exceed 12.2 kg/m^2. The increase in pressure caused by vent closures with greater mass/area ratios can be determined in accordance with E6.2 or NFPA 68 Annex F.

E6.2 Mass-gravity closure

The maximum allowable mass of any deadweight type of closure can be calculated from the formula—

$$P = \frac{S}{V^{\frac{1}{3}}}\left(0.42K\frac{M}{R} + 2.8\right) \text{ (Refs [2] and [3])}$$

Validated experimentally within the following limits:

P <35 kPa

$V \leq 3$ m^3

$S \geq 2$ m/s