WHAKARATONGA IWI

FIRE EMERGENCY

NEW ZEALAND

ASSESSING FIREFIGHTING WATER SUPPLIES

University of Canterbury

January 2020

The aim of this research was to develop a framework for estimating the energy release rate from developing building fires to provide evidence to support development of the new code of practice for firefighting water supplies.

Fire and Emergency New Zealand Research Report Number 175

ISBN Number 978-1-92-728738-5
ISSN Number 2703-1705

University of Canterbury, Department of Civil and Natural Resources Engineering (2020). *Estimating energy release rate from real fires for use in Assessing Firefighting Water Supplies* (Report No. 175). University of Canterbury, Christchurch, NZ: Fire and Emergency New Zealand.

This research was commissioned by Fire and Emergency New Zealand and undertaken by independent researchers. Publication does not indicate Fire and Emergency New Zealand's endorsement of the findings or recommendations.

Estimating Energy Release Rate from Real Fires for use in Assessing Firefighting Water Supplies

C M Fleischmann, V Ye, and J Spinks
University of Canterbury
Department of Civil and Natural Resources Engineering

1. INTRODUCTION

Water is the single most common fire suppression agent used throughout the world. As a suppression agent, water extinguishes a fire by cooling, removing oxygen, etc. For major fire incidences, large quantities of water may also be necessary for protecting the adjacent properties that are exposed to significant thermal radiation. At major fires, the total amount of water required can be millions of litres that must be supplied at rates greater than a 1000's of lpm (litres per minute). Fire and Emergency New Zealand (FENZ) has a critical need for large quantities of water in order to meet their statutory requirements. However, such flow rate requirements are rarely needed, and often municipal water supply design is governed by the required fire flow.

In New Zealand, with its large rural and geographically diverse population, large fire flow requirements can be even more onerous on rural building owners and small communities. There is a responsibility on the part of all regulators to develop regulations that are appropriate to the hazard but not excessively onerous. In addition, any regulation should provide an evidence base to support methodologies used in the regulation. NZS4509:2008 *New Zealand Fire Service firefighting water supplies code of practice*[1], currently sets requirements for water supplies for buildings in New Zealand. NZS 4509:2008 New Zealand Fire Service firefighting water supplies code of practice is the current methodology used for calculating the required fire flows in New Zealand. The code of practice uses a scientific basis for the firefighting water supplies but is limited by the existing information on accurate estimates of the energy release rate of real fires. Thus, NZS4509 may not be accurately estimating the water storage requirements.

The aim of this research is to develop a framework for estimating the energy release rate from developing building fires to provide evidence in support the firefighting water supplies published in NZS4509:2008 *New Zealand Fire Service Firefighting Water Supplies Code of Practice*. The objective is to apply fundamental concepts of compartment fire dynamics along with post fire investigation data and video observations to estimate the energy release rate from building fires. This report is divided into two main parts:

1. A review the existing methods for calculating the required fire flows for both New Zealand and internationally to better understand the currently available knowledge and techniques available.
2. The application of compartment fire dynamics for calculating the energy release week in building fires.

In the application of fire dynamics section is further divided into three sections:

1. Zero-order approximations –relies on vary little understanding fire dynamics and requires a minimum amount of training to be implemented.
2. First order approximations – relies on a basic understanding of compartment fire dynamics and would require a trained and experienced fire investigator.
3. Second order approximations – relies on an advanced understanding of compartment fire dynamics, advanced algebra, and estimated 16 hours of additional training.

The report has been setup in this way in order to provide FENZ with options to consider when choosing a strategy for estimating the heat release rate from compartment fires. As the level of analysis increase in complexity, so does the time and resources required to implement the strategy. In some cases, the increased level of complexity and resources, may not give a sufficient increase in the accuracy of the analysis to justify the expense.

2. EXISTING METHODS FOR CALCULATING FIRE FLOWS

NZS4509 was largely based on the research by Davis[2] and was developed to apply the best available information at the time of its development. When NZS4509 was written, there was a comprehensive review of the existing methodology both domestically and internationally reported by Davis[2]. Subsequent to the Davis report, there have been a comprehensive review by the Fire Protection Research Foundation (FPRF) titled Evaluation of Fire Flow Methodologies, released in January 2014[3]. Also, noteworthy, is the research in this area by Grimwood[4] et al reviewing more than 5000 urban and rural fires that is also been reviewed as part of this report. Below is a review of the 17 international methodologies for estimating fire flows. Each method is briefly outlined, and appropriate references are supplied if the reader would like a more detailed information. Methodologies that have been applied in New Zealand, have been included in a separate section below.

2.1 International Methods

2.1.1 Insurance Services Office (ISO) Method[5]

The ISO method is widely applied in the USA. It contains a mathematical model to estimate the required fire flow for extinguishment by considering the factors including construction types, building area, combustibility of the building occupancy, inter-building fire exposure, communication between buildings and the presence of fire protection measures[6] (Myburgh, 2012). The required fire flow for an individual, non-sprinklered building fires calculated using Equation 1 (ISO Properties., 2012).

$$\text{NFF} = (C_i)(O_i)[1.0 + (X + P)_i] \qquad (1)$$

where NFF is the Needed Fire Flow) in GPM (gallons per minute) C_i, O_i, X and P are factors which represents construction type, occupancy type, exposure condition, as well as communication between buildings.

Based on a field database, the ISO method also suggests some general durations of firefighting suppression for different types of occupancy (Insurance Services Office, 2012), including:

The fire-flow duration for commercial properties is 2 hours for Needed Fire Flows (NFF) up to 2,500 GPM (160 L/s) and 3 hours for Needed Fire Flows of 3,000 (190 L/s) and 3,500 GPM (220 L/s).

- The fire-flow duration for 1- and 2-family dwellings with an effective area in excess of 4,800 square feet is 2 hours for Needed Fire Flows (NFF) up to 2,500 GPM (160 L/s) and 3 hours for Needed Fire Flows of 3,000 and 3,500 GPM (190 to 220 L/s).
- The fire-flow duration for 1- and 2-family dwellings with an Effective Area of 4,800 square feet (450 m^2) or less is 1 hour.

Hence, the total water volume demand is estimated by multiplying the required fire flow rate with the application durations. However, the application of this method also contained some uncertainties. According to Torvi et. al.[7], the theories behind the mathematical models are not explained well as it did not give any assumptions that were made in the creation of this model and the method does not consider the available ventilation in the methodology.

2.1.2 International Fire Code (IFC) Method[8]

The International Fire Code (IFC) method is built up by using a list of tabulated needed fire flow (NFF) values, which were derived through a simplified ISO method. Compared to the ISO method, the IFC method is more focused around the factors of construction types as well as the installation of sprinkler system. The example reference tables for the required fire flows are shown in Figure 1, below. However, the source of data was not clearly identified. Thus, the validity and accuracy of the method is not available.

TABLE B105.1(1)
REQUIRED FIRE FLOW FOR ONE- AND TWO-FAMILY DWELLINGS, GROUP R-3 AND R-4 BUILDINGS AND TOWNHOUSES

FIRE-FLOW CALCULATION AREA (square feet)	AUTOMATIC SPRINKLER SYSTEM (Design Standard)	MINIMUM FIRE FLOW (gallons per minute)	FLOW DURATION (hours)
0–3,600	No automatic sprinkler system	1,000	1
3,601 and greater	No automatic sprinkler system	Value in Table B105.1(2)	Duration in Table B105.1(2) at the required fire-flow rate
0–3,600	Section 903.3.1.3 of the *International Fire Code* or Section P2904 of the *International Residential Code*	500	$^1/_2$
3,601 and greater	Section 903.3.1.3 of the *International Fire Code* or Section P2904 of the *International Residential Code*	$^1/_2$ value in Table B105.1(2)	1

For SI: 1 square foot = 0.0929 m^2, 1 gallon per minute = 3.785 L/m.

TABLE B105.1(2)
REFERENCE TABLE FOR TABLES B105.1(1) AND B105.2

FIRE-FLOW CALCULATION AREA (square feet)					FIRE-FLOW (gallons per minute)[b]	FLOW DURATION (hours)
Type IA and IB[a]	Type IIA and IIIA[a]	Type IV and V-A[a]	Type IIB and IIIB[a]	Type V-B[a]		
0-22,700	0-12,700	0-8,200	0-5,900	0-3,600	1,500	2
22,701-30,200	12,701-17,000	8,201-10,900	5,901-7,900	3,601-4,800	1,750	
30,201-38,700	17,001-21,800	10,901-12,900	7,901-9,800	4,801-6,200	2,000	
38,701-48,300	21,801-24,200	12,901-17,400	9,801-12,600	6,201-7,700	2,250	
48,301-59,000	24,201-33,200	17,401-21,300	12,601-15,400	7,701-9,400	2,500	
59,001-70,900	33,201-39,700	21,301-25,500	15,401-18,400	9,401-11,300	2,750	
70,901-83,700	39,701-47,100	25,501-30,100	18,401-21,800	11,301-13,400	3,000	3
83,701-97,700	47,101-54,900	30,101-35,200	21,801-25,900	13,401-15,600	3,250	
97,701-112,700	54,901-63,400	35,201-40,600	25,901-29,300	15,601-18,000	3,500	
112,701-128,700	63,401-72,400	40,601-46,400	29,301-33,500	18,001-20,600	3,750	
128,701-145,900	72,401-82,100	46,401-52,500	33,501-37,900	20,601-23,300	4,000	4
145,901-164,200	82,101-92,400	52,501-59,100	37,901-42,700	23,301-26,300	4,250	
164,201-183,400	92,401-103,100	59,101-66,000	42,701-47,700	26,301-29,300	4,500	
183,401-203,700	103,101-114,600	66,001-73,300	47,701-53,000	29,301-32,600	4,750	
203,701-225,200	114,601-126,700	73,301-81,100	53,001-58,600	32,601-36,000	5,000	
225,201-247,700	126,701-139,400	81,101-89,200	58,601-65,400	36,001-39,600	5,250	
247,701-271,200	139,401-152,600	89,201-97,700	65,401-70,600	39,601-43,400	5,500	
271,201-295,900	152,601-166,500	97,701-106,500	70,601-77,000	43,401-47,400	5,750	
295,901-Greater	166,501-Greater	106,501-115,800	77,001-83,700	47,401-51,500	6,000	
—	—	115,801-125,500	83,701-90,600	51,501-55,700	6,250	
—	—	125,501-135,500	90,601-97,900	55,701-60,200	6,500	
—	—	135,501-145,800	97,901-106,800	60,201-64,800	6,750	
—	—	145,801-156,700	106,801-113,200	64,801-69,600	7,000	
—	—	156,701-167,900	113,201-121,300	69,601-74,600	7,250	
—	—	167,901-179,400	121,301-129,600	74,601-79,800	7,500	
—	—	179,401-191,400	129,601-138,300	79,801-85,100	7,750	
—	—	191,401-Greater	138,301-Greater	85,101-Greater	8,000	

Figure 1 - The reference tables of required fire flows from the IFC method (International Fire Codes, 2018)

2.1.3 National Fire Protection Association (NFPA) 1142 - Water Supplies for Suburban and Rural Fire Fighting Method [9]

Chapter 4 of the document outlines the method for calculating the minimum water supply for basic structural firefighting. This method assumes the fire flow is proportional to the volume of the fire cell and it is designed to be used for firefighting suppression only[3]. The estimation is based on arbitrary values for Construction Class (0.5 to 1.5) and Occupancy Classification (1 to 7, 1 is most hazardous) and any exposure hazards. The detailed relationship between these variables are shown equation 2 & 3 below.

$$\mathrm{WS}_{min} = \frac{VS_{total}}{OHC} \times \mathrm{CC} \qquad \text{for structure without exposure hazards} \qquad (2)$$

$$\mathrm{WS}_{min} = 1.5 \times \frac{VS_{total}}{OHC} \times \mathrm{CC} \qquad \text{for structure with exposure hazards} \qquad (3)$$

where WS_{min} stands for minimum water requirement (gallons), VS_{total} is the total volume of structure (m^3), OHC is the occupancy hazard classification number and CC is the construction classification number.

Noted in the document is the minimum required water supply for structures without exposure hazards is 2,000 gal (7,600 L) and the minimum quantity for structures with exposure hazards is 3,000 gal (11,400 L). The total firefighting water usage under each standardized fire flow rate can be approximated using Table 1.

Table 1 - The NFPA 1142 estimation method[7]

Total Water Required (L)	Fire flow rate (L/s)
< 9500	16
9500 – 38000	32
38000– 76000	47
>= 76000	63

The recent study from NFPA Fire Protection Research Foundation[3] noted that by using a GAP analysis, it was found that the total water required for the 1- and 2- family dwellings by NFPA 1142 was less than the estimated total water usage at the real fire scenes. For example, for a designed fire scenario in a 3-storey residential building with the total floor area of 975 m^2, the actual applied fire flow was found as 110 L/s which was significantly higher than that required by NFPA 1142 (i.e. around 47 to 63 L/s). However, since the actual field data are still quite limited at this stage, a further study is expected.

2.1.4 The International Wildland-Urban Interface Code (IWUIC) Method[10]

This method is only applicable to wildland-urban interface (WUI) communities and it must be approved by authorities having jurisdiction (AHJ) (International Code Council, 2012). The method was developed for specific fire zones and considered more viable than for typical urban building fires. In order to simplify the design and deliver a conservative estimation, it was decided to assume that the rate of firefighting water suppression is only related to the type and floor area of the building. For example, for one- and two-family dwellings, with floor area is less than 3,60m^2 square feet (3600 ft^2), the required fire flow rate is 1,000 GPM (63 LPS) for 30 minutes. For floor areas greater than 360 m^2, a 95 L/s (63 lps) fire flow rate must be provided for 30 minutes, floor areas[10].

2.1.5 Ontario Building Code (OBC) Method[11]

The Ontario Building Code Method is designed for estimating the required quantity of water as well as the related flow rate for firefighting in non-sprinklered buildings (Ministry of Municipal Affairs and Housing, 2005). The minimum quantity of water required (Q in gal) is calculated using the following equation:

$$Q = (0.00749) \times K \times V \times [1.0 + (S_{side\ 1} + S_{side\ 2} + \cdots + S_{side\ n})] \quad (4)$$

where K represents a water supply coefficient which ranges from 10 to 53 based on the construction types of the building, V is the total volume of building in a unit of ft^3 and S_{side} is the individual spatial coefficient from property line exposures on all sides of the building. The code noted that the maximum fire flow for any water supply is retricted to 2,400 GPM (150 L/s), the individual spatial coefficients shall be less than or equal to 0.5 and sum of all spatial coeffecients [i.e. $1.0 + (S_{side\ 1} + S_{side\ 2} + \cdots + S_{side\ n})$)has a maximum value of 2.0.

Nevertheless, as per the SFPE (NZ) Technical Publication TP 2007/1[31], this estimated fire flow rate is assumed to be limited between 30 and 150 L/s. Hence, this method might not be suitable for large firecells.

2.1.6 FIERA system Water Requirements Model[7]

The Fire Evaluation and Risk Assessment system (FIERAsystem) is a numerical system which used for modelling light industrial fire scenarios developed by the Canadian National Research Council. The model considers the factors which include geometry of the building, possible fire scenarios, sensitivity of fire detectors, suppression systems, adjacent buildings, response time, combined heat release rate (HRR) of all fires in the building, cooling capacity of firefighting water and working efficiency of intervention by fire departments. It needs to be noted that compared to the above methodologies, only this method considers the possible impacts of fire control. However, in the limited literature review we were unable to find any case studies applying the FIERA model.

2.1.7 French D9 Technical Document Method[12]

The French D9 Technical Document contains a number of tabulated minimum fire flow requirements for home, office, public assess buildings and industrial buildings. The detailed information about those reference tables can be found in ref [12]. It needs to be highlighted that for the industrial risk design, more complex estimates should be consider the influence of risk categories, storage arrangement (e.g. divided buildings) and internal intervention (e.g. fire safety systems). The minimum fire flow rate is 264 GPM (17 lps) and the minimum operational duration for flows of industrial building fires is generally set to be 2 hours, except in special fire circumstances.

2.1.8 UK National Guidance Document on the Provision of Water for Firefighting Method[13]

The method which explained in the UK National Guidance Document is very similar to the IFC method and French D9 Technical Document method, provides a list of fire flow values for different occupancy. Guidelines for flow requirements are included in Appendix 5 of the document: *National guidance document on the provision of water for firefighting (3rd edition)*[13]:

- Housing:

(1) No more than 2 floors: a minimum of 8 L/s through any single hydrant

(2) More than 2 floors (multi-occupied): a minimum of 20 to 35 L/s through any single hydrant

- Industry:

(1) Up to one hectare: 20 L/s.

(2) One to two hectares: 35 L/s.

(3) Two to three hectares: 50 L/s.

(4) Over three hectares: 75 L/s.

- Shopping, offices, recreation and tourism: a minimum flow of 20 to 75 L/s to the development site
- Education, health and community facilities:

(1) Villages: >= 15 L/s per hydrant

(2) Primary schools and single storey health centres: >= 20 L/s per hydrant

(3) Secondary schools, colleges, large health and community facilities: >= 35 L/s per hydrant

2.1.9 Iowa State University Method (ISU) [14]

The ISU method was developed from hundreds of fire tests conducted by Iowa State University in the 1950s. The method considers oxygen depletion and was designed based on the heat absorption capability of water, the heat production from the volume of air in a given open area as well as the steam generation which is required to displace air in a given volume. The required flow given in Equation 5 is expressed in GPM where V is the volume of firecell in the unit of ft^3:

.

$$\mathrm{RFF} = \frac{V}{100} \tag{5}$$

The flow requirement only relates to the size of fire room and it is assumed that the total volume of the building can be filled with steam. Royer[14], who used to work for the Iowa State University, wrote in *Fire Engineering* Magazine that the application of this method was often misunderstood in following perspectives.

- The formula should not be altered regardless of the fuel load or type. This does not apply to the application stage. There is a difference between planning and application.
- Only the largest single open area of the structure should be used. The method does not take into account other water that may be needed for other parts of the structure or for exposures.
- Do not use this model in tactical sense. This method can work if fire is only in closed compartments.
- Do not underestimate the role of steam.

This approach has significant limitations as highlighted in ref[7] that showed that the ISU method may 'predict unrealistically high-water flow rates for large fires' due to the great room volume.

2.1.10 Thomas[15], and Baldwin[16], and Särdqvist[17], Methods

A continuous developing model had been used by three researchers Särdqvist, Thomas and Baldwin. The simple approach assumes that the fire flow is only a function of the horizontal fire area (A) in square feet. Although each researcher analysed multiple fires, the factor and power on the horizontal areas are different, as shown in Table 2.

Table 2 - Flow equations for Thomas, Baldwin and Särdqvist simple power law relationship.

Researchers	Number of Fire Analysed	Tested Fire Covered Area, A [ft^2]	Fire Flow Estimations [GPM]	Fire Flow Estimations [L/s]
Thomas[14]	48	2,150 to 650,000	$24.2 \times A^{0.5}$	$1.53A^{0.5}$
Baldwin[16]	134	214 to 130,000	$4.09 \times A^{0.66}$	$0.258A^{0.66}$
Särdqvist[17]	307	<= 10,720	$4.17 \times A^{0.57}$	$0.263A^{0.57}$

2.1.11 Illinois Institute of Technology Method (IIT)[18]

The IIT method was developed from a dataset of 134 past fire incidents in the Chicago area which may have been the same dataset used by Baldwin in reference 16. The method is similar to the previous Särdqvist[17], Thomas[15], and Baldwin[16] Methods, which the fire flow (FF) is directly linked with the fire area (A_{fire}). However, the method is slightly more complex and is divided into residential and non-residential buildings fires as shown below:

$$FF = 0.00009A_{fire}^{2} + 0.5A_{fire} \quad \text{for residential occupancies} \quad (6)$$

$$FF = (-1.3 \times 10^{-5})A_{fire}^{2} + 0.42A_{fire} \quad \text{for other occupancies} \quad (7)$$

The method had also been found to contain the following constraints which may influence its prediction accuracy.

- It appeared to be invalid for large buildings (i.e. greater than 1200 m^2) due to the negative coefficient for non-residential occupancies[3].
- It has the advantage of examining fire flow requirements individually for each building. However, in cases where further construction of buildings has taken place it could result in an overestimation of the required fire flow[19].
- The method does not include the water requirements for exposure protection purpose[20].

2.1.12 National Fire Academy Method (NFA)[21]

The NFA method is modified from the previous ISU method by considering the possible impacts of fire floors (e.g. accumulated heat effects from different level of floors). The mathematical expression of NFA method is given as Equation 8 below

$$\text{NFF} = \left(\frac{L \times W}{3} + Exposure\ Charge\ [Note: 25\%\ of\ basic\ fire\ flow\ per\ exposure\right) \times percentage\ of\ involvement \quad (8)$$

where NFF standards for needed fire flow [GPM], L (ft) and W (ft) represent length and width of the involved floor respectively.

However, according to the related research NFPA Fire Protection Research[3] the application of NFA method could be only reliable if four or fewer floors are involved by fire.

2.1.13 The Grimwood Method[4,22,23]

The most comprehensive research in the UK has been done by Grimwood and is reported in ref 4. Grimwood et. al. has developed and refined the 'tactical flow-rate (TFR)' for estimating the fire flow which providing the smallest total water volume if possible. In the report *Fire-fighting Flow-rate*[22], their analysis of the effects of hoseline size, phases of fire (e.g. gaseous vs fuel-phase), cooling efficiency of streams, latent heat of vaporization and other parameters have been taken into account in the estimating the firefighting water requirement. Based on this analysis, the firefighting water demand can be calculated using:

- large compartment: minimum tactical flow (i.e. 6.67 L/s) should overcome the fire-front even as the fire is developing. If the fire has spread to involve structural components; walls; beams; floors; roofs, breaching compartmental boundaries etc, the higher flow of 600GPM may be needed
- Small compartment: The required fire flow rate [L/s] = 0.066667*floor area. However, this formula was only verified for room size within 50m^2 and 600m^2 and with 2.5m high ceilings

This works has been further developed in ref *23* published in 2014, that states 'once a fire reaches a 20-30 MW level of heat release (depending on accessibility to the fire and resource availability), a minimum flow-rate of 8.33 to 12.5 L/s must be delivered directly onto the fire before it spreads beyond control' and the water application must be operated in the first 20 minutes. The most comprehensive, statistical study on fire flows reported in 2015, analysed of 5,401 UK building fires between 2009 to 2012. Grimwood developed the methodology to estimate the fire flow rate demand (L/s) for additional occupancy types as shown below, where the fire area is in unit of m^2.

Table 3 - Grimwood method

Occupancy	Fire Flow Estimations [L/s]
Dwellings	$4.732 \times Fire\ Area^{0.44}$
Industrial	$8.265 \times Fire\ Area^{0.51}$
Public infrastructure (school, hospital)	$3.849 \times Fire\ Area^{0.57}$

However, its limitations of this method are also discussed in the SFPE (NZ) TP2007/1[24], which it is only 'valid for fire covered area from 50 to 600 m^2. The flow formula is for suppression only and does not include any allowance for exposure external to the burning firecell'.

2.1.14 The Fire Underwriters Survey (FUS)[25] Method

The Fire Underwriters Survey method is the most popular estimate method in Canada. The method is based on research and empirical fire protection experience. It determines the required fire flow (RFF) as a function of the building characteristics, that considers the construction type, floor area, number of storeys, occupancy, level of exposure risk, combustibility of the building and the presence of fire protections (i.e. sprinklers). The primary fire flow design (F) is expressed as:

$$\text{F}\ [litre/min] = 220 \times C \times \sqrt{\sum A_{floor}} \tag{9}$$

where A is the total floor area for all levels and C is a coefficient which represents different building materials (e.g. 1.5 for wood frame constructions, 1.0 for ordinary constructions, 0.8 for non-combustible constructions and 0.6 for fire-resistant constructions). The method also bounds the fire flow not to exceed 756.7 L/s nor be less than 33.3 L/s.

2.1.15 The Integrated Uncertainty Analysis Method[26]

The National Taipei University of Technology and Taoyuan County Fire Department conducted a fire flow study by using an integrated uncertainty analysis. This study was designed to develop a simple assessment model to utilise the heat release rate ($\dot{Q}$) of building fires for estimating the related water requirements for firefighting purpose. The theoretical water demand is calculated using the following relationship:

$$\text{m}_c = \frac{\dot{Q}}{C_p \times \Delta T} = 3.3 \times 10^{-4} \times \alpha \times (t_{in})^2 \times t_s \tag{10}$$

where C_p represents the specific heat of water, ΔT is the change of temperature (kelvin), t_{in} is the approximate duration of fire department intervention, α is the fire growth coefficient for various building classification, t_s is the total suppression period and m_c is the water required for firefighting (kg). Oher factors that can affect the fire flow that were not incorporated in the analysis include:

- Building usage
- Number of building stories
- Floor area and volume of a building
- Exposures
- Fire station location

The authors summarize their findings from the one hundred of random case studies:

- 'the largest (water) volume required was 234 metric tons
- the least volume 3 metric tons
- most common water demand for water suppression was 18 metric tons, which occurred 18 times
- in 80% of the cases, firefighting water volume was less than 68 metric tons of water'

2.1.16 Carleton University Method[20]

The methodology was developed by assuming that the water supply quantity for offensive and defensive firefighting operations are different (Hadjisophocleous & Richardson, 2005). The total flow required is the sum of the flow required during both offensive and defensive tactics. During the offensive operation, they stated the required water flow rate could be estimated as

$$Fire\ Flow_{offensive} = \frac{60 \times HRR}{2.6 \times \eta_0} = \frac{0.058 \times w'' \times \sqrt{A_f}}{\eta_0} \qquad (11)$$

where HRR is the heat release rate of fire area, η_0 represents the cooling efficiency of water for offensive operation, w'' represents fire load density for various occupancy and A_f represents fire area.

While for the defensive operation, the required water flow is calculated based on a radiation exposure by considering a view factor in the calculations as shown below.

$$Fire\ Flow_{defensive} = \frac{\sum F_{u,total}}{\eta_d} \times \left(0.005 \times w'' \times \sqrt{A_f}\right) \qquad (12)$$

where η_d represents the cooling efficiency of water for defensive operation and $\sum F_{u,total}$ is the sum of view factors for four exposing building faces.

The cooling efficiency of water (η)is usually selected in a range of 0.3 to 0.6 for different types of nozzle applied. The detailed guidance for determining this factor can be found in the document of *An Engineering Approach to Fire-Fighting Tactics* from Lund University[17].

The authors also compared their method with ISO[5] and OBC[11] methods in many case study evaluations. However, as explained by the authors, 'it is difficult to undertake a meaningful comparison, due to the different objectives of the three methodologies. The new methodology appears to provide results that are consistent with the OBC and ISO methods, given their objectives. The new methodology is not, however, intended for use for special occupancy hazards such as high rack storage and flammable liquids facilities.

2.2 New Zealand Methods

2.2.1 The GIS Method[27]

This research used an interesting application of Geographic Information System (GIS) and hydraulic modelling system to assess fire flow requirements and the possible impact on sprinkler system. The project was supported by the Christchurch City Council.

According to the current New Zealand fire design code *SNZ PAS 4509:2008 (Standards New Zealand, 2008),* the required firefighting flows are set as 'from 12.5 L/s for sprinklered family homes, to 200 L/s for large or high-risk industrial buildings. Particularly high-risk structures may require a calculation to estimate the required firefighting flow, which could potentially exceed 200 L/s. However, after applying GIS to the provided land zoning and building area information database (note: consider sprinkler installations as well), the results showed a number of buildings in suburban Christchurch might need higher fire flows, especially for schools, hospitals or rest home facilities. The detailed mapping of fire flow demands is presented below, where the red zone represents the areas where the fire flow is required to be 200 L/s and the green area requires 25 L/s. Moreover, the author also explained that 'due to the uncertainties in assessing both required and available fire flow, a pass was recognized where available flow was 120% of the required flow or greater'.

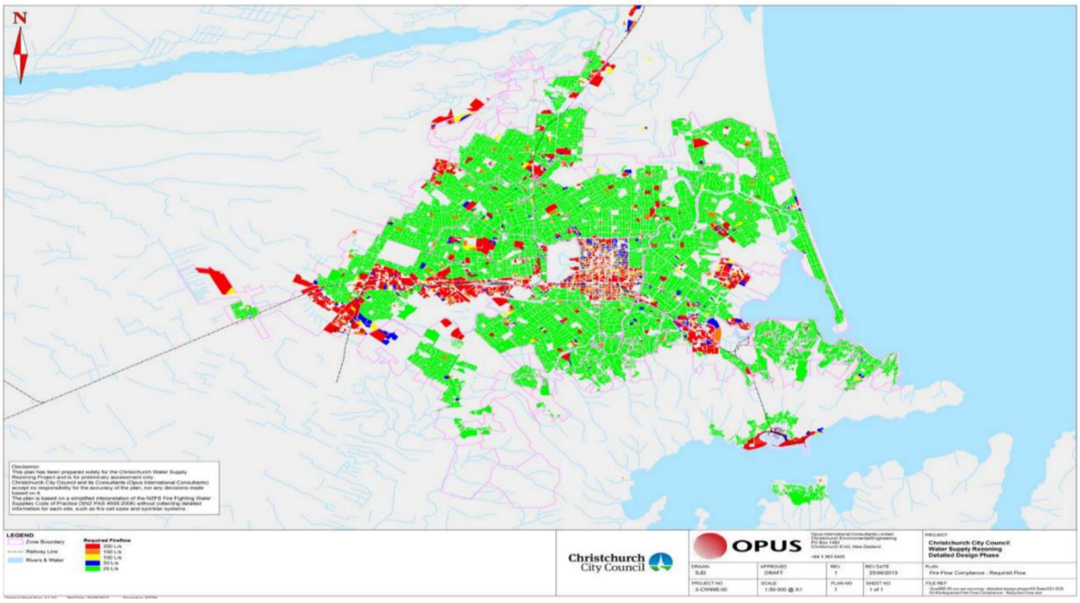


Figure 2 - - The fire flow rate estimations for regions in Christchurch, NZ[25]

2.2.2 New Zealand Society of Fire Protection Engineers (SFPE) Method[28],[29]

The SFPE (NZ) method is described in technical publications TP 2004/1[28] and TP 2005/2[29]. TP 2004/1 shows the estimation of the water flow requirements during firefighting operations and TP 2005/2 is used to calculate the water storage criteria for firefighting purposes. As stated in TP2004/1 (Society of Fire Protection Engineers, 2004), the required fire flow demand (F) is modelled by applying the following general equation:

$$\text{F}\,[L/s] = \frac{k_F \times Q_{max}}{k_w \times Q_w} \approx 6.1\ \times Q_{max} \tag{13}$$

where k_F and k_W represents the heating efficiency of fire and cooling efficiency of water suppression (Note: both estimated to be 0.5). Q_{max} is the peak heat release rate of fire (MW) and Q_w is the absorptive capacity of water at 100°C which is set as a constant value of 2.6 MW/L/s. Based on this model, a further study found that fire flow requirement could also be influenced by the fire-covered floor area. The relationship could be plotted as shown in Figure 3. Thus, Equation 13 was modified to account for the floor area as shown Equation 14:

$$\text{F}\,[L/s] = 0.00741 \times \left(e_f \times A_f\right)^{0.666} \tag{14}$$

where e_f is the fire load energy density and A_f is the floor area of the fire room. In this model, the floor areas ranged from 100 to 5,000 m^2 and the fire load energy density that was selected to be 400, 800 and 1200 MJ/m^2 as shown in Figure 3.

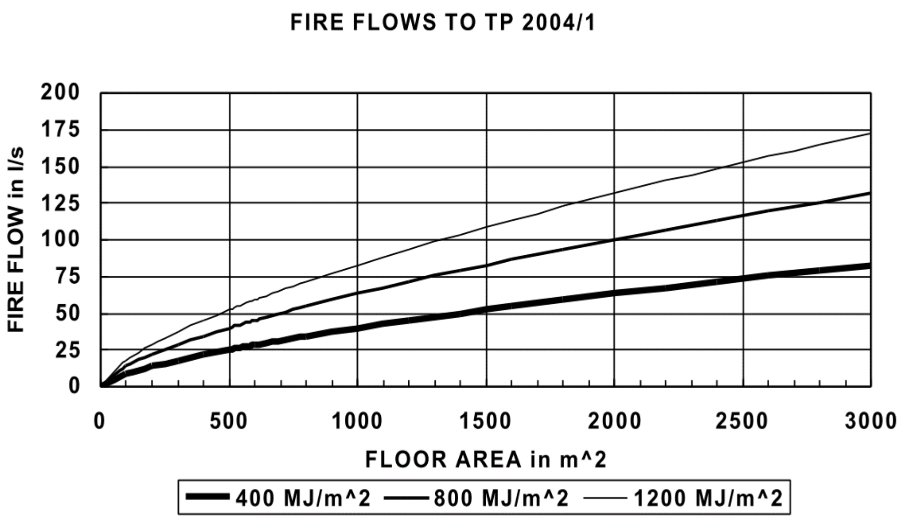


Figure 3 – Plot of fire flow rate versus fuel load energy density (MJ/m^2) using TP2004/1 method for predicting the firefighting water flow requirements assuming a heat of combustion to be 18 MJ/kg.

In the document of TP2005/2 (Society of Fire Protection Engineers, 2005), the firefighting water storage required with the corresponding time of flow are estimated by three different methods, which include Arbitrary Time Method, Arbitrary Fire Intensity Method and Firecell Volume Method. Due to this research project focuses more on the practical demand of firefighting water application, the detailed information about the related water storage could be found from the original TP2005/2 document.

2.2.3 New Zealand Fire Engineering Design Guide Method (FEDG)[30]

The FEDG method is very similar to the above SFPE (NZ) method, which the required fire flow is related to the theoretical heat absorbing capacity of water and steam. However, in the FEDG method, the cooling efficiency of the water is no longer assumed to be constant but could also be varied under different temperatures as shown figure shown below (Fire Engineering Design Guide, 2001).

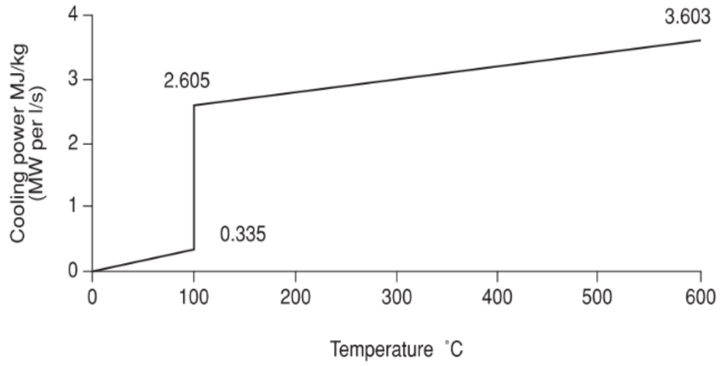


Figure 4 - Plot of the cooling efficiency of water as a function of temperature.

The FEDG suggested that the actual requirement of firefighting water demand could be well predicted if the following factors were known,

- The expected fire growth rate curve;
- The fire intensity at the time the fire is attacked;
- The expected duration of the fire and the peak fire intensity;
- The water supply required to match the peak fire intensity; and
- The ratio of applied water to required water for the intended firefighting water application system.

An international study published as a technical publication from SFPE (NZ) in 2007[31] suggested the use of FEDG method is 'only [applicable] to small firecells. This is because in the FEDG design, the model of burning rate estimation was developed through testing small firecells which the floor area was of the order of 10 m^2. Therefore, the model might not able to predict the scenarios in large firecells, especially for those floor areas which exceed 500 m^2.

2.2.4 SNZ PAS 4509 Methods[1]

NZS 4509:2008 New Zealand Fire Service firefighting water supplies code of practice (Standards New Zealand, 2008) is the most common methodology that has been applied in New Zealand. In this methodology, the total water quantity considers both firefighting and exposure protection.

As given in Appendix J of NZS4509, the procedures for determining the water flow requirements:

1. Estimate the maximum heat release rate (Q_{max}) as described in Appendix H that includes the effects of ventilation factor.
2. Calculate water flow rate required for firefighting ($M_{water} = 0.58* Q_{max}$)
3. Calculate the exposure protection, M_{exp} by using the total exposure area and water wetting rate
4. Calculate total water flow rate required, $M_{total} = M_{water} + M_{exp}$
5. Assess the adequacy of the available firefighting water

Once the required fire flow rate has been determined, the burning duration is estimated using the general equation from the Appendix J8:

$$t_{fire}[s] = \frac{\Delta H_c \times M_{fuel}}{Q_{max}} \quad (15)$$

Where t_{fire} is the burning duration (s), ΔH_c is the heat of combustion, M_{fuel} is the mass of fuel in firecell and Q_{max} is the maximum heat release rate of fires.

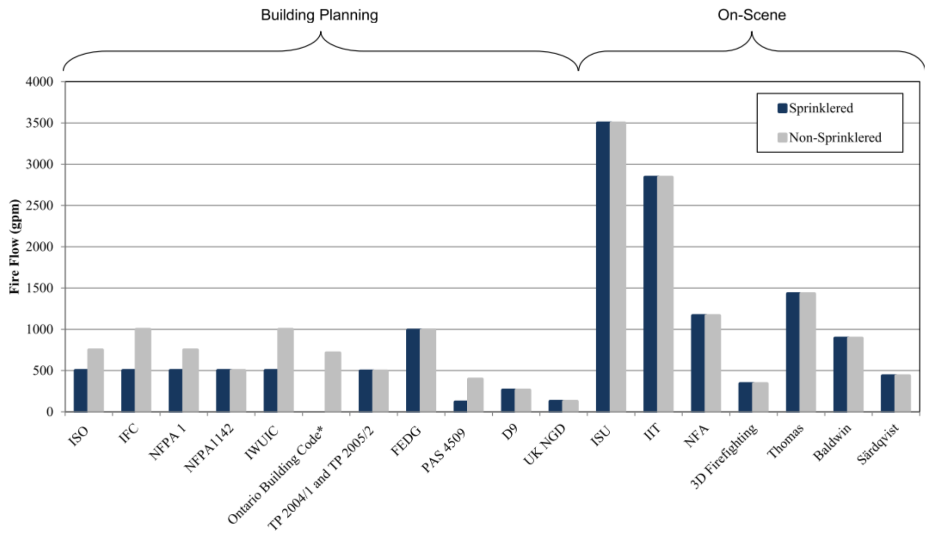
2.3 Comparison between Common International Methods

Comparisons between different methodologies for calculating fire flow requirements can be challenging because of the significant differences in the frameworks. Some methods rely on the fire dynamics where other depend on historic statistical data and others are of unknown origin. In many cases, the methods may approach the problem from fundamentally different perspectives, one being a city planning perspective where the details of the building are unknown. Another approach relies on the expected hazard based on zoning restrictions and even another approach looks at the details of the building even going as far as considering the details of the ventilation openings. Regardless of the various perspectives, Table 4 does provide a useful comparison of all the methodologies discussed in this report. The rows give the name associated with methodology and the columns give the parameters that are used to determine the fire flows. Another difficulty in interpreting/comparing methods are the interdependent nature of some of the parameters such as some methods require the FLED where other use occupancy type which often defines the FLED. Reviewing Table 4 it can be seen that there commonalities between many methods, yet there is no wide spread agreement on the parameters that should be included when estimating the required fire flows.

Table 4 - Comparison of parameters used in determining the fire flow requirements for different methodologies outlined in this report.

	Parameters																						
Tools/organization/	Floor area	Compartment Volume	Fuel load energy density	Ventilation	Occupancy	Storage arrangement	Fire Alarm System	Suppression System	Proximity to fire station	Location (Rural/Urban)	Exposure	Construction type	Geometry of Building	Heat release rate	Response time	Adjacent building	Effectivenss of fire service operation	Building Materials	Duration of fire department interventio	Cooling Efficiency of Water	Heating Efficiency of Fire	Absorptive Capacity of Water	Firefighting Equipment inside building
SNZ PAS 4509	X				X		X	X						X									X
New Zealand Society of Fire Protection Engineers (SFPE)	X		X											X						X	X	X	
New Zealand Fire Engineering Design Guide (FEDG)														X						X		X	
Insurance Services Office (ISO)					X						X	X											
International Fire Code (IFC)	X							X				X											
National Fire Protection Association (NFPA) 1142		X			X						X	X											
The International Wildland-Urban Interface Code (IWUIC)	X							X															
Ontario Building Code (OBC)		X									X	X											
FIERA system Water Requirements							X		X		X		X	X	X	X	X						
French D9 Technical Document Method	X				X	X			X			X	X				X						
UK National Guidance Document on the Provision of Water for Firefighting	X				X																		
Iowa State University Method (ISU)		X																					
Särdqvist, Thomas, and Baldwin Methods	X																						
Illinois Institute of Technology Method (IIT)	X																						
National Fire Academy Method (NFA)	X																						
The Grimwood Method	X				X																		
The Fire Underwriters Survey (FUS)	X																	X					
The Integrated Uncertainty Analysis Method												X							X				
Carleton University	X		X											X						X			

Although the comparison between the different methodologies is challenging and can vary significantly depending on the assumptions made about the specific building used for comparison, it is still useful to show some comparison of the methods. Because the focus of this study is not solely on the topic of required fire flows, this report will rely on the available comparison in the recent literature. The most comprehensive and recent comparison is reported in the NFPA Fire Protection Research Foundation (FPRF) report by Benfer & Scheffey, 2014[3]. In the FPRF report, the authors apply 18 different methods, including NZS4509, to a 140 m² & 325 m² single family home for both the sprinklered and unsprinklered cases. In the FPRF report they draw the distinction between the methods that are developed for building planning and the on-scene methods that rely on firefighting experience or statistical fire incident data.



The results are shown in Figure 5 & 5 and demonstrate that there can be more than an order of magnitude difference in the results of the various methods.

Figure 5 - Fire flow calculation results for a 325 m² single-family home in presence/absence of a sprinkler system[3].

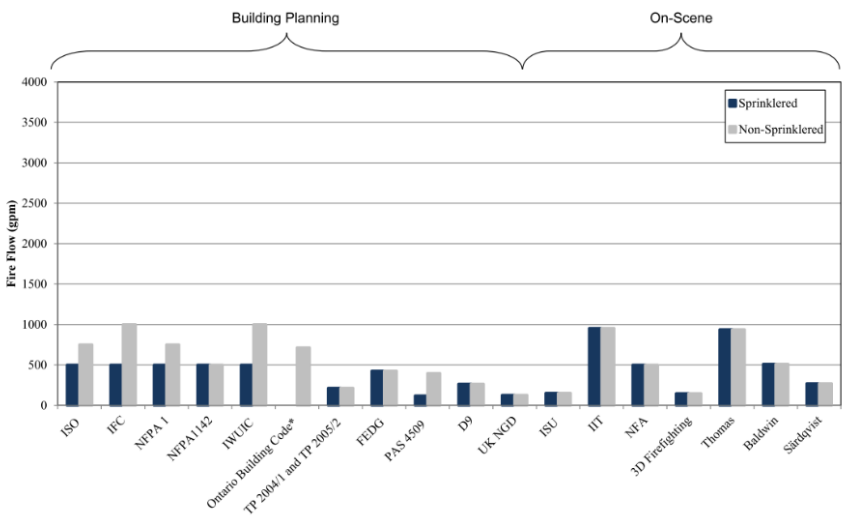


Figure 6 - Fire flow calculation results for a 140 m² single-family home in presence/absence of a sprinkler system[3].

2.4 Conclusion - Existing Methods for Calculating Fire Flows

The existing methods of calculating fire flows, can be divided in two approaches as highlighted in the FPRF report. The building planning methods that typically rely on multiple parameters relating to the building, occupancy & fire safety features and on scene methods that only use the building or firecell area. The results of this review show that there is no commonly accepted method for calculating fire flow requirements and there is a little agreement in the methods or results of the existing methods.

FPRF report has suggested that the National Fire Incident Reporting System (NIFRS) could be used estimate the actual fire flow used in the fire incident. In fact, much information required about the incident and building are included in the database structure. However, it has been the experience of this author, that the data is often not reported or includes obvious inconsistencies in specific records. In addition, the current NFIRS structure does not include the details about the fire flows used at an incident. Changes to the NFIRS data structure include:

- Total flow use
- Amount of water used in suppression activities
- Amount of water used in other activities (overhaul etc)
- Duration of fire suppression operation
- Duration of other operations
- Maximum flow rate used in the incident

Using such information would represent a significant improvement to the current data that is collected and would allow for significantly improved statistical analysis of fire incident data. Such data would allow for improved evidence-based methods for calculating the required fire flow. However, the collection of this level of detail is not currently possible and would require the following changes within FNZE:

1. Changes to the to the NFIRS database structure.
2. Modification to fire apparatus to measure and record as a function of time, the water flow used at fire incidents.
3. Additional training to the users for the equipment and data collection personnel.

3. ESTIMATING THE HEAT RELEASE RATE FROM REAL FIRES

It is clear from the review of current methodologies for calculating required fire flows for buildings, that there is no consistent approach to the problem and little evidence base for existing methods. Although the FPRF report recommends an evidence-based approach through the changes in the information collected in the NFIRS system. They do not give any guidance on collecting better information about the magnitude of the fire beyond the assignment of the FLED to the specific occupancy. The remainder of this report explores the idea of collecting and processing of post fire information so that the heat release rate can be estimated from actual fire incidence.

Previous work on estimating the heat release rate from actual building fires has been limited. Even for planned fire experiments such as the Underwriters Laboratories Firefighters Safety Research Institute (ULFSRI) the most active large-scale fire research organization burning actual buildings, heat release rate data is limited to gas burner experiments or single residential scale rooms under calorimeters. Studies that full scale one and two- story houses in their lab and onsite studies in building due for demolition do not allow for measuring the building heat release rate. Therefore, any full-scale building heat release rate studies rely on estimates based on expert judgement not measurements and typically not even analysis.

The remainder of this report focuses on a framework for estimating the heat release rate for analysing fires in real building. The methodologies are described based on the level of approximation from zero to second order approximation. In the zero-order approximation, the analysis requires very little information apart from the building/fire area and the use of the building. No detail about the fire or fire compartment is required. Very little knowledge would be required by the individual caring out the analysis. First order approximation requires understanding of the building area and a limited fire investigation to gauge the extent of damage, amount of fuel involved, and the approximate burn time. This would require a limited amount of additional training and could be carried out by a fire investigator. In the second order approximation, detailed fire dynamics analysis may be undertaken to estimate the heat release rate and would likely require a fire engineer or a trained investigator. However, in some of the techniques mentioned in this report still require additional research in order to develop existing methods for application to real fires. The order assigned is in no way critical of the researcher identified in this report but points that the limitation that the researchers were constrained by in their work. The accuracy of any research is only as good as the data available for analysis. Thus, the research is considered to have been conducted using the best available knowledge and understanding at the time.

3.1 Zero order approximation

Unfortunately, there have been few studies that have attempted in a systematic way to estimate the heat release rate from building fires. Traditionally, fire investigations have focused on finding the cause of the fire. If the fire is not suspicious in nature and relatively minor in damage, the incident may only be investigated by the officer in charge. In the case large or suspicious fires, a more formal investigation may be carried out by a fire safety officer with the specific fire investigation training and the incident may be referred to the police if the fire is suspicious. Typically, if a fire is not suspicious the investigation will stop once the cause of the fire has been determined to a reasonable degree of confidence by the investigator/fire office. In some cases, it may not be possible to determine the cause of the fire and the fire may be classified as "undetermined". Rarely, are the fire growth and development investigated in any detail beyond the normal origin and cause investigation.

A review of the fire investigation research reveals that there have been few studies that have attempted to estimate the energy release rate from fires. Studies such as Grimwood[4] relied largely on UK Fire and Rescue National Incident Reporting to estimate the heat release rate . Fire incident data provides only limited information that can be used for estimating the energy release rate from a fire. In Grimwood's study, more than 5000 working building fires were analysed. This included more than 4000 urban and 1000 rural fires. Although the fire service collects data on all emergency responses this research specifically focused on fires and did not include derelict buildings, exterior roof fires, or chimney fires. The data specifically targeted internal fire damage and where water was deployed by a hose reel or main fire stream/monitor.

However, in the analysis the authors had to make some simplifying assumptions. Fires were classified as private dwelling or “all other building”. The area of the building was divided in various classification such as 50-100m^2 and then an average value was assumed, in this case 75m^2. The authors then estimated the fire size assuming a 7% opening factor which gives a heat release rate per unit area, often symbolically referred to as (q”), as q”= 200-250 kW/m^2 floor area. The precise value used were not reported so a range is inferred by back calculating from value given for the fire size and areas. The value of 200-250 kW/m^2 assumes a fully involved space with stoichiometric burning and 7% of the floor area as ventilation area. Note that this estimate is considered to be a peak value for the burning and does not include water required for exposure protection or the impact of compartment enhancement nor reduction due to limited ventilation.

To apply this approach to crudely estimate the heat release rate for an area/firecell involved, the area of burning would need to be estimated either by direct measurement, fire incident data collected for fire area, or area categories such as Grimwood et. al. had done. The accuracy of this method would be greatly improved by direct measurement of the area burned in the fire by the investigator. The method could also be improved by refining the q” based on the fuel involved and/or property use of the building. This method assumes the fire is post- flashover although the area times heat release rate per unit area (HRRPUA) approach could be used for pre-flashover fires but burning area would require direct measurement by the investigator and the fuel involved would also be required to improve the accuracy.

Results from the zero-order analysis is only able to provide the maximum heat release rate within the building and would not be able to estimate the growth rate nor the heat release rate that may occur outside the compartment such as external fire plumes from a window. Uncertainty of applying this zero-order approximation is considered to be quite high and may be as high as several times the calculated value. When using this value, the researcher should provide an estimate of the uncertainty based on their understanding of the fire dynamics, assumptions they have to make for the specific analysis, and their confidence in the accuracy of the area measurements.

3.2 First order approximation

The first order analysis requires significantly more detail about the building involved and the specific event timing, and the observations made by the person that discovered the fire. This methodology is based on the research by Holborn et. al.[32], “An analysis of fire sizes, fire growth rates and times between events using data from fire investigations”. The research relied on London’s “Real Fire Library”. The data used had been input by fire investigators, not operational personnel and had some level of filtering. The data incorporated 5 years data from 2000-2004 and include 2044 residential homes and 464 other building fires. Data used in the analysis include:

a) Event times:
   i) time of ignition of the fire,
   ii) time the fire was discovered,
   iii) time the fire brigade was first called out,

  iv) time of fire brigade arrival at the scene of the fire.
b) Fire areas:
  i) area of the fire at the time of discovery,
  ii) fire area when the fire brigade arrived at the scene of the fire,
  iii) final fire damaged area.
c) Type of occupancy in which the fire occurred.
d) Ignition source.
e) First material involved in the fire.
f) Any first-aid fire-fighting actions taken by the occupants

Not all of the required data was recorded for every fire, so not all incidents could be used in the analysis. In the case of fire growth estimates, 481 residential dwellings and 164 "other buildings" were analyzed. The data was analyzed to estimate the fire growth rate[33] using the commonly used engineering approximation:

$$\dot{q} = \alpha t^2 \qquad (16)$$

where:

q- fire heat release rate (kW)

α- fire growth constant (kW/s^2)

t – time (s)

In engineering terms, the α value is categorized into one of 4 fire growth rates[34] based on the α value derived in oxygen depletion calorimetry experiments where critical time (t_c) is the time for the fire to reach 1055 kW.

Ultra-fast α=0.188, tc=75s

Fast α=0.0469, tc=150s

Medium α=0.0117, tc=300s

Slow α=0.00293, tc=600s

In Holborn, et. al. they defined ranges centered around the original classification and defined a new fire growth rate as “very slow” fires. The definitions used by Holborn et al is given in Table 5

Table 5 - Fire growth parameters used for classification used in Holborn et. al.

Growth rate class	Range of α (kW/s^2)	Time to reach 1055 kW (s)
Very slow	< 0.000412	>1600
Slow	0.000412–0.006594	400–1600
Medium	0.006594–0.026375	200–400
Fast	0.026375–0.1055	100–200
Ultra fast	>0.1055	<100

The α value was estimated from the data collected by the fire investigators as defined in the following relationship:

$$\alpha = \frac{\dot{q}''\left(A_1 t_1^2 + A_2 t_2^2\right)}{t_1^4 + t_2^4} \tag{17}$$

Where:

$\dot{q}''$ - is the average rate of heat release per unit area of the fire (kW/m^2);

A_1 - area of the fire when it was first discovered (m^2);

A_2 - the area of the fire when the fire brigade arrived (m^2);

t_1 - the time interval between ignition and discovery of the fire (s)

t_2 - the time interval between ignition and fire brigade arrival (s)

The $\dot{q}''$ was taken as 250kW/m^2 for all buildings except retail (500kW/m^2) and warehouse/storage (1000kW/m^2). The $\dot{q}''$ values shows the authors recognized that certain building uses, i.e. retail and warehouse/storage are likely to be more severe fire than other property uses. This is an improvement on the zero-order approximation above.

The results from the 481 residential dwellings that included all of the required data for analysis are shown in Table 6. The results demonstrate how relatively rare, rapidly developing fires are in residential building were <4% of the fires were classified as fast or ultrafast.

Table 6 – Number and percentage of dwelling fires sampled in each fire growth parameter class.[32]

Number and percentage of dwelling fires sampled in each fire growth parameter class

Fire growth parameter class[a]	Frequency	Percent (%)
Very slow	142	30
Slow	276	57
Medium	49	10
Fast	13	3
Ultra fast	1	<1
All	481	100

[a] Based on a sample of 481 fires in dwellings where the value of α could be estimated, the fire brigade took some form of action and a specific ignition time was estimated.

Similar results can be seen for "other buildings" in which the growth rate could be estimated in 164 fire are reported in Table 7. It is interesting to note, although the sample sizes are too small to be considered significant, that the in facilities where you can expect 24hr staffing such as care homes, hospitals and even hotels, only slow or very slow fires were found in this study. However, in retail and industrial buildings, including warehousing, had the fast or ultra-fast fires. Overall in "other buildings" only 10% were considered to be fast fires.

Table 7 - Number of fires in other buildings belonging to each fire growth parameter class by occupancy group[33].

No of other building fires	Fire growth parameter class					
Occupancy group	Very slow	Slow	Medium	Fast	Ultra fast	Total
Care homes	5	4	—	—	—	9
Factories	4	7	1	3	1	16
Higher/further education	1	4	—	—	—	5
Hospitals	7	10	—	—	—	17
Hotels	5	7	—	—	—	12
Licensed premises	4	10	2	—	1	17
Offices	6	11	2	—	—	19
Public buildings	2	6	1	1	—	10
Retail	4	18	9	4	2	37
Schools	6	9	—	1	—	16
Warehouse	—	2	1	2	1	6
Other building fires (all)	44	88	16	11	5	164
Other building fires (%)	27%	54%	10%	7%	3%	100%

[a]Based on a sample of 164 fires in other buildings where the value of α could be estimated, the fire brigade took some form of action and the uncertainty in the time of ignition was 15 minutes or less.

Beyond the growth phase, Holborn et al also reported the final fire damaged area for "other buildings" as shown in Table 8. Unlike Table 6 & Table 7 which reported number of fires out of the 441 fires and 164, respectively. Table 8 gives % of fires that exceeds defined areas including 0-1 m^2, 1-10 m^2, 10-100 m^2, and >100 m^2. A similar table was not reported for dwelling fires but can be inferred from Figure 7 which show the complimentary cumulative distribution function versus fire damage area.

Table 8 – Percentage of fires in other building to each fire damage size group by occupancy type

Other buildings	Fire damage area				
Occupancy group[a]	Less than 1 m^2 (%)	1–10 m^2 (%)	10–100 m^2 (%)	100 m^2 or more (%)	Number of fires
Care homes	65	29	6	—	17
Factories	13	55	23	9	47
Further education	29	43	29	—	14
Hospitals	47	50	3	—	30
Hotels	45	53	3	—	38
Licensed premises	26	56	16	2	50
Offices	30	44	22	3	63
Public buildings	12	53	24	12	34
Retail	17	53	27	3	94
Schools	35	38	26	—	34
Warehouses	—	40	30	30	20
All[b]	26	49	20	5	441

[a] Rows may not add to 100% due to rounding error.
[b] Total based on 441 fires investigated in other buildings where the fire damage area was specified.

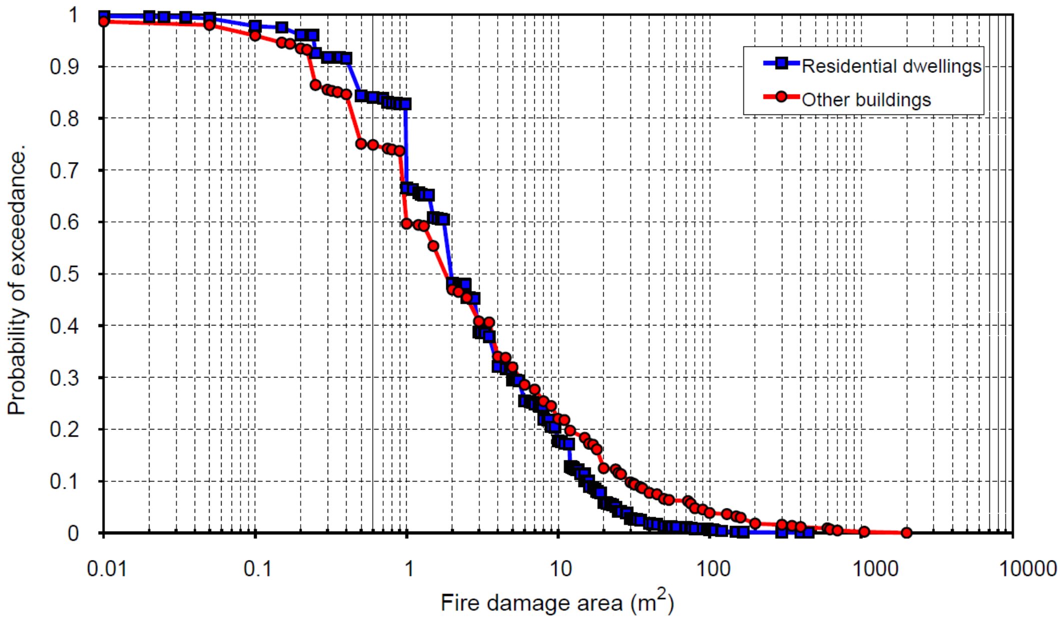


Figure 7 – Complimentary Cumulative Distribution Function for fire damage area for the samples of fires investigated in both residential dwellings and other buildings.[32]

The first order analysis would be expected to be a significant improvement over the zero-order method. However, would require significantly more data from each fire and would require special training for the investigators. A full set of data that is required complete level of analysis for the fire growth rate and maximum fire size, would only be available for a limited number of fires where there is reliable eyewitness observation for estimating the time of discovery and fire area at discovery. Information from eyewitnesses would require additional time for the investigator to conduct detailed interviews. To conduct such detail in fire investigation would require additional training and commitment of the fire investigators.

3.3 Second Order Approximation of Heat Release Rate

The second order approximation relies on both a through understanding of fire investigations and detailed understanding of fire dynamics. Unlike the previous methods discussed above, the second order approximation is most likely suited to a degreed fire engineer or a highly trained fire investigator with a detailed understanding of fire dynamics.

This method is broken down into parts: 1) techniques that can be applied using our current understanding, and 2) techniques that are understood but lack the validation to be applied at the time this report was written. The techniques discussed in part 2 apply the current level of fire dynamics estimate the heat release rate and burning duration. The techniques have not yet been adequately researched to assess their application and determine their uncertainty methods. Future research will be required to truly validate these methods.

Currently, the UL Firefighter Safety Rescue Institute (FSRI) is undergoing unprecedented growth and expansion of their research capabilities that will include fire investigations. FSRI has recently released a report titled: "Impact of Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures"[35] . In this report the authors demonstrate the impact of ventilation can have on the fire development and damage patterns left behind. However, they stop short of developing the tools necessary to estimate how long the fire had been burning from the severity damage patterns. As FSRI expands their research focus beyond firefighter safety, they will work to provide more tools for fire investigation, and it is hoped that some of the techniques discussed here will be included in their future research.

3.3.1 Information required for a second order analysis

In order to apply any of the techniques described in this section, detailed information will need to be collected during the fire investigation process. This information is not included in the NFIRS reporting and would require trained fire investigator or fire engineer to collect the data. All of the information that would need to be collected is listed here in one place. Not all techniques discussed below require all of the information listed here but it is preferred to have all of the data gathering detail in one place for the second order approximation. The intention here is not to define the information required in a fire investigation. For information on conducting a fire investigation the reader should consult NFPA921[36] or any number of textbooks on the topic. The intention here, is to highlight the additional information that may need to be collected and may not be reported in a standard investigation fire report.

a. Sketch of Building dimension
    i. Length
    ii. Width
    iii. Height
    iv. Number of stories
b. Compartment(s) involved in the fire dimensions
    i. Length
    ii. Width
    iii. Height
    iv. Vent sizes window, door, roof, etc
        1. Width
        2. Height
        3. Sill height
c. Char pattern sketch on each surface
d. Depth damage map (char, calcination, etc)
e. Estimate FLED available
f. Estimate FLED consumed
g. Estimate of Q" for space or item ignited
h. Extent of exposure protection required
i. Dimensions of large fuel packages in fire compartment(s)

B) Photos
    a. Exterior of all sides of the building labelled north, etc
    b. Photos of each wall where fire was present labelled north, etc
    c. Photo of ceiling labelled with north arrow
    d. Photos of floor labelled with north arrow
    e. Photos of damage patterns of interest
    f. Photos of major packages involved in the fire

Consideration should be given to using a 360 camera that allows the full damage pattern to be visualized. A 360 camera is no substitute for a high-resolution camera and good lighting, a 360 camera can make the piecing together of photographs easier and allows the investigator to easily observe the room and then seek details in other high-resolution images.

Beyond the information given above, interviews with eyewitnesses should also be obtained where possible. As in the first approximation, obtaining evidence on the size of the fire when discovered and when the firefighters arrived are vital to estimating the fire development especially in the pre-flashover stage. Without eyewitness accounts, some of the desired estimates may not be able to be achieved.

3.3.2 *Applying Expert Judgement to Estimate Heat Release Rate per Unit Area ($\dot{q}''$)*

Applying the Heat Release Rate per Unit Area (HRRPUA) is same technique that was used in the first order analysis except that engineer/investigator is expected to apply expert judgement when chose $\dot{q}''$ (kW/m^2) and not simply taking an average for the class of the building. In spaces with several prominent fuel packages multiple $\dot{q}''$ may be used along with the floor area occupied by the specific fuel package Table 9 provides some exemplar values for individual palletized commodities from the SFPE Handbook of Fire Protection Engineering[39].

The $\dot{q}''$ should not be confused with q'' which is symbolic for the FLED or fuel load energy density (MJ/m^2). In this case the $\dot{q}''$ should be taken from the literature on full scale experiments of fuel items. Although, $\dot{q}''$ is report in the cone calorimeter test, the cone experiments should be considered a material value and used for comparative purposes. A UK perspective on $\dot{q}''$ can found in the recent paper in Fire Technology titled: "A Review of Design Values Adopted for Heat Release Rate Per Unit Area"[37] The values in ref [37] are for a particular property use.

Table 10 provides a $\dot{q}''$ taken from the literature and summarized in ref [37]. A range of values for each property use is provide from the literature. These values are considered to be design values which are often taken at the 80-90% values for the range. Data on sets for $\dot{q}''$ are often limited in such studies and may not be statistically significant to be representative of the "real world". If this methodology is to be adopted by FENZ , then they should consider developing their own $\dot{q}''$ database for postfire analysis that is developed over time and is based on their experience as it evolves.

Table 9 - Heat release rate per unit area ($\dot{q}''$) for palletised storage[38].

Commodity	Storage Height (m)	Peak HRR (kW/m^2)
Wood pallets, stacked (6-12% moisture)	0.46 m	1248
Wood pallets, stacked (6-12% moisture)	1.52	3745
Wood pallets, stacked (6-12% moisture)	3.05	6810
Wood pallets, stacked (6-12% moisture)	4.88	10214
Mail bags, filled, stored	1.52	400
Cartons, compartmented	4.57	2270
PE trash barrels in CB cartons	4.57	28,900
PS foam insulation	4.21	26,000
PS jars in compartmented CB cartons	4.11	16,600
PS foam meat trays, wrapped in paper, in CB cartons	4.9	11,700
PS foam meat trays, wrapped in PVC film, in CB cartons	4.88	10,900
PVC bottles in compartmented CB cartons	4.63	8,510
PS cups in compartmented CB cartons	5.94	8,030
PS cups in compartmented CB cartons	4.42	6,580
PS tubs in CB cartons	4.17	6,440
PP tubs in compartmented CB cartons	4.26	5,870
PE botlies in compartmented CB cartons	4.2	5,330
PS toy parts in CB cartons	4.48	5,210
PE botlies in CB cartons	4.41	4,810
PS cups in compartmented CB cartons	2.9	4,420
PS cups in compartmented CB cartons	2.9	4,420
PS cups In compartmented CB cartons	2.9	4,420
CB cartons, double tri-wall, metal liner	5.99	3,260
CB cartons, double tri,wall, metal liner	4.47	2,520
Compartmented CB cartons, empty	4.51	2,470
CB cartons, double tri-wall, metal liner	4.47	2,250
CB cartons, double tri-wall, metal liner	2.95	1,680
CB cartons, double tri-wall, CB cartons, double tri-wall, metal liner	2.95	1,680
CB cartons, double tri-wall, metal liner	2.95	1,490
PU rigid foam insulation	4.57	1,320
Fiberglass (polyester)shower stall in carton	4.6	1400
PE letter trays filled, stacked on cart	1.5	8500
PE and PP film in rolls	4.1	6200
CB- cardboard, PE-Polyeythylene, PP-polypropylene, PU-polyurethane		

Table 10 - HRRPUA from literature taken from ref [37]

Occupancy	HRRPUA (kW/m^2)
Shops	270–1200 (maximum)
Offices	150–650 (maximum)
Hotel rooms	250 (average)
Residential	320–570 (maximum)
Industrial	90–620 (average)
Storage/stacked commodities	400–20,000 (maximum)

3.3.3 Estimating energy release rate based on ventilation into the compartment

The heat release rate $\dot{q}''$ discussed above, is fundamentally based on free burning calorimetry data that assumes that the fire has an infinite amount of air available. This assumption may be valid depending on the fire, especially in the pre-flashover phase and in large well-ventilated spaces with limited fuel available. However, in most cases a compartment fire can be expected to become ventilation limited which means the heat release rate is controlled by the amount of oxygen that can enter the compartment. When fire enters into a ventilation limited state, flames are often seen extending outside vents because there is not enough oxygen for the fire to burn inside the compartment. The fuel gasses that burn outside the compartment have little effect on the fire intensity inside the compartment. The most severe fires occur when fuel released inside the compartment is stoichiometrically proportional to the oxygen that is entering the compartment with the air. Although fires are rarely in this idealized state, this condition is often assumed to provide the most intense and longest lasting fire. When excess fuel is released inside a compartment, some of the fuel will not be able to react because all of the oxygen is consumed and the excess fuel acts as an inert gas until it can mix with oxygen outside the compartment where it burns. If there is excess oxygen in the compartment, then the excess oxygen acts to dilute the combustion gases and reduce the temperature thus reducing the fires intensity.

Estimating the energy release rate within a fully developed post flashover compartment based on the amount ventilation was first suggested by Kawagoe[39] in 1958. Kawagoe recognized that the mass loss rate for timber cribs in fully developed fires correlated well with the now well-known opening factor $A_O\sqrt{H_O}$. Rockett[40] later found, using Bernoulli's equations and assuming a hydrostatic pressure profile, that above 150°C mass of the air $\dot{m}_{Air}$ can be estimated assuming:

$$\dot{m}_{Air} = 0.5A_O\sqrt{H_O} \tag{18}$$

Using Rockett's correlation, assuming the fire is consuming all of the oxygen entering the compartment and applying the principle of oxygen consumption calorimetry provides a simple correlation for the energy release rate within a compartment of:

$$\dot{Q}_{FD} = 3\left(\frac{\text{MJ}}{\text{kg}_{\text{air}}}\right)\left(0.5A_O\sqrt{H_O}\right) = 1.5A_O\sqrt{H_O}\,(\text{MW}) \tag{19}$$

Where:

A_O – Area of the opening (m^2)

H_O – Height of the opening (m)

Equation 19 is only applicable to fully developed fires with vertical openings (windows and doors). Compartments with multiple openings can be analysed by using weighted average for all vertical openings as given in equation 20:

$$h_{eq} = \frac{\sum A_{vi}\sqrt{H_{Oi}}}{\sum A_{vi}} \quad (m) \tag{20}$$

To estimate the flow in a horizontal opening (roof vent) requires that the upper layer temperature and layer height to be known in order to estimate the energy release rate. Such analysis requires an iterative solution and does not lend itself to basic fire dynamic analysis. In such cases, a more detailed fire modelling analysis should be considered. Additional information for calculating the vent flows for horizontal vents can be found in *Enclosure Fire Dynamics*[41].

3.3.4 Using Depth of Damage to Estimate the Burning Duration

Damage patterns as a tool for fire investigation has been applied since fire investigation began as a discipline with the first fire investigation textbook was published in 1945[42]. Recently damage patterns have come under criticism and the fire investigation community has had to re-examine long held beliefs on interpreting fire damage patterns[43]. The most comprehensive review on the topic was carried out by Gorbett et. al.[44] and provides a comprehensive review on the topic. Even with the long history and existing research base, the complex nature of compartment fires can make it difficult to interpret fire damage patterns. The recent study by the ULFSRI on damage patterns provides evidence of the effect of ventilation on damage patterns and how difficult it can be to interpret damage patterns in fire investigations. Recent work has also focused on measuring the depth of calcination of gypsum wallboard after a fire in order to quantify fires intensity to assist in determining the area of origin[45,46]. However, there is currently no method to use depth of damage as a quantifiable measure of fire duration. Depth of calcination is currently only used as a relative measure within a compartment. A greater depth of calcination simply indicates that a surface has been exposed to a greater cumulative heat flux when compared to another location within the compartment.

The same point can be made for the charring of timber. According to Babrauskas, "the present state of affairs has been such that there is not much agreement on what quantitative interpretation, if any, can be placed on such patterns".[47] In a subsequent article, Babrauskas[48] concludes:

> Under conditions of severe, post-flashover room fires (but not absolute worst-case extreme conditions), heavy-timber or similar members that have no gaps or joints will char at similar rates to those found in fire-resistance furnace tests—roughly 0.5–0.8 mm/min. Thus, unless unusual factors are known to be involved (e.g., combustion of metals), it may be assumed that charring rates in an actual fire will not exceed these test values

Babrauskas goes on to point out that for thinner timber such as walls and floors are not as consistent as large timber members and warns against inferring too much from char patterns.

In the list information to be collected during the investigation (given above) the depth of calcination and char has been recommended. This information can be useful when looking at the overall damage to a fire compartment and may assist with the investigation. Although at the time this report was written, there is insufficient knowledge to use this information quantitively, the information may be able to be analysed in the future.

3.3.5 Analysing Damage Patterns on Gypsum Wallboard to Estimate Heat Release Rate[49]

In preflashover fires, there is often a pattern left behind by the initial fuel item on fire, especially from items in close proximity to a wall. Figure 8 shows the damage pattern from 10 replicate test burning a 300mm square metal pan with 500ml of petrol as the fuel. The images show how consistent the pattern of the burned paper can be. Madrzykowski[49], studied the repeatability of damage pattern on gypsum wallboard from preflashover fires for three fuels, natural gas (mostly methane), petrol (gasoline), and polyurethane foam. In this research, the damage patterns were found to be repeatable and correlate well to flame height measurements.

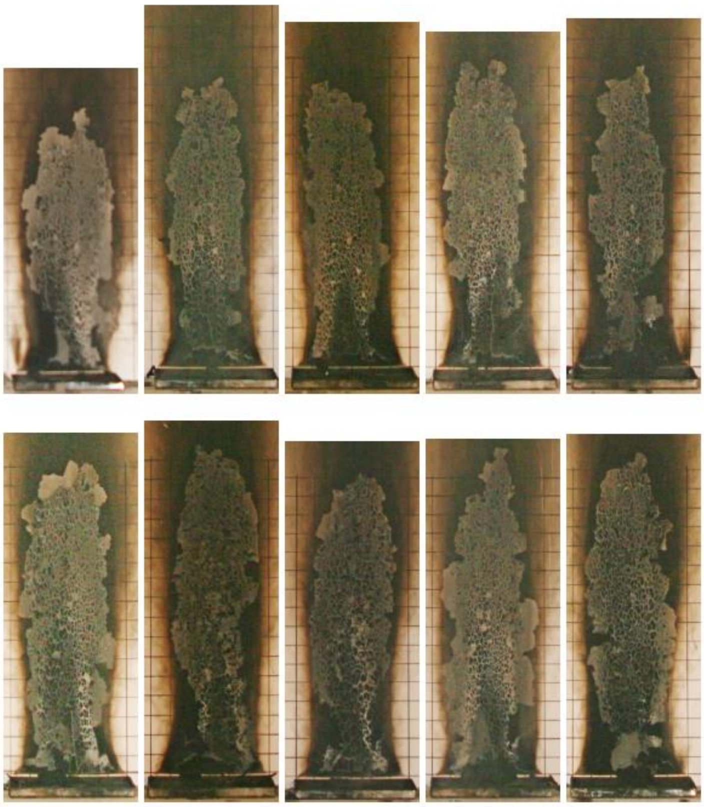


Figure 8 -Photographs of the fire patterns from 10 replicate petrol pool fires against insulated wall construction experiments[49].

Madrzykowski also investigated the ability to predict the experimental flame height using the well-known Heskestad equation[50]:

$$h_f = 0.235\dot{q}^{2/5} - 1.02D \qquad \text{Eq. 21}$$

Table 11 shows the comparison of the results for the flame height measurements from both photographs taken during the experiments and time averaged video analysis compared with the fire pattern measurements and Heskestad predictions. The measured values are shown with the +/- 95% confidence limits and (%) uncertainty given parenthetically. Heskestad's median flame height calculations are presented as a range based on the uncertainties of the average peak heat release rate of each fuel type. The 0.235 constant in Heskestad's equation was also corrected to account for the difference in the fuel properties. The results are encouraging for the natural gas and petrol but disappointing for the more complex polyurethane foam.

Madrzykowski also points out that the results are from well controlled fires and intended to be at a near steady-state condition. For the natural gas, the fires exhibited a near constant heat release rate. The petrol pools showed a growth phase, steady phase, and a burnout phase. While the polyurethane foam gave a growth and burnout phases with no discernible steady state phase which explains some of the uncertainty in the results. Madrzykowski also warns that the steady state nature of the experiments does not account for the transient heating of the gypsum wallboard which is required before the paper burns off and a damage pattern becomes evident.

Because of this transient requirement, Madrzykowski does not recommend using the damage pattern in the inverse of Heskestad's equation to predict the peak heat release rate. Therefore, this approach is not recommended here without further study.

Table 11 Comparison of the median flame height measurement results with the fire pattern heights and the Heskestad predictions.

Method	Flame Heights (m)		
	Natural Gas	Gasoline	Polyurethane Foam
Photographic	0.70 ± 0.23 (33%)	0.84 ± 0.28 (33%)	0.46 ± 0.23 (50%)
Video Based	0.70 ± 0.11 (15%)	0.70 ± 0.1 (14%)	0.47 ± 0.16 (34%)
Fire Pattern	0.74 ± 0.12 (16%)	0.83 ± 0.15 (18%)	0.24 ± 0.12 (50%)
Heskestad (range)	0.94 to 1.06	0.65 to 0.93	0.36 to 0.72

3.3.6 Image Processing to Estimate Preflashover Energy Release Rate

Inverting Flame Height Correlation to Estimate Energy Release Rate – Calculating the flame height has been a topic of fire researcher for more than four decades. Several correlations exist in the literature and the review article by Beyler's[51] is the most comprehensive review on the topic of fire plumes that includes the flame height correlations. There are many correlations covering several fuel geometries including gas burners, pool fires, wall flames, corner flames, and line sources, Beyler points out that there is general agreement among the researcher that the flame height is proportional to $\dot{q}^{2/5}$. Typically, the correlations include a constant of proportionality that is between 0.18 and 0.23 when $\dot{q}^{2/5}/D > 16.5$. Most of the existing correlation for the flame heights have been developed for 2D sources which make the diameter (or equivalent diameter for non-circular shapes) of the fire well defined. However, for three dimensional items, such as furniture, defining the diameter can be difficult to define.

Figure 9 shows the complex flame shape formed by a piece of furniture on fire with the flame spreading on the seat, back, and arms. To further complicate the problem, fire on the seat will burn through at some time and spill the molten foam and fabric onto the floor below the chair and then burn as a pool fire in combination with chair frame. This complex burning behaviour is described in ref [52] and makes it challenging to define the flame.

In this report, the $\dot{q}^{2/5}$ dependence is assumed to hold for upholstered furniture; however, the constant of proportionality must be determined. To determine the constant of proportionality 10 items of furniture were chosen from the New Zealand Combustion Behaviour of Upholstered Furniture (NZCBUF) study,[53, 54] 6 single-seater and 4 two-seater. Figure 10 shows the upholstered furniture burned in the NZCBUF study.

The experimental flame height was determined by observing 5 seconds of video (125 frames) frame by frame and recording the flame height. This was done every 15 seconds over the period of from 1 minute after ignition to 4 minutes after ignition. This is the period of most intense burning. The experimental values were adjusted to account for the burn through of the seat cushion. Once the fire was observed on the videotape to have formed a pool under the chair 0.5 m was added to the experimental flame height.

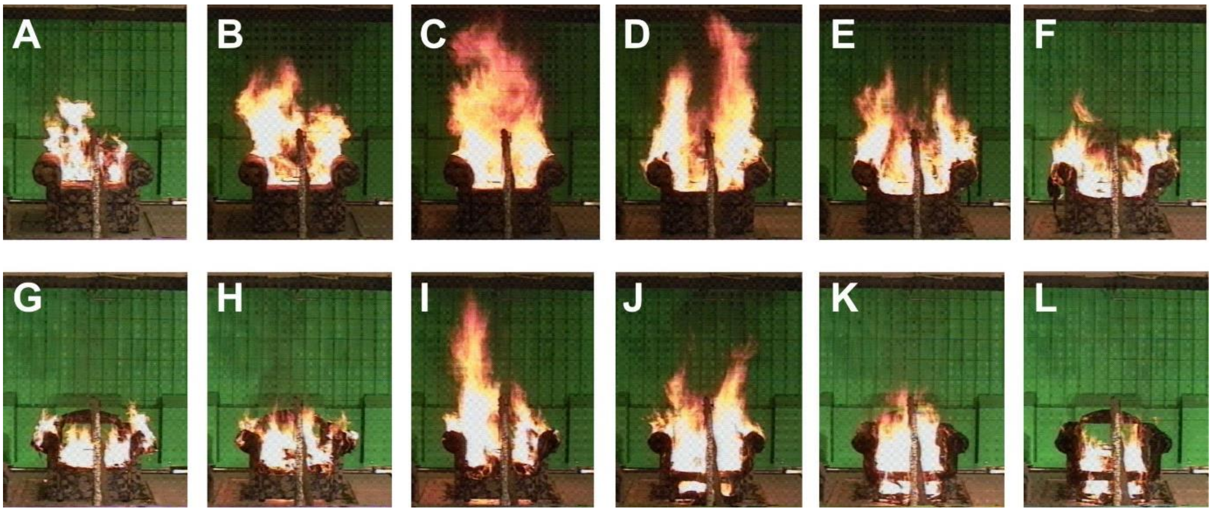


Figure 9 - Series of photographs showing the changing flame shapes throughout the burning cycle for the chair.

Figure 10 - Photographs showing the items of furniture burned in the flame height experiments. Item 1 is the two-seat version of the sample tested and is representative also of items 2 to 5, with only the fabric varying.

In the original study[55], the chair experiments showed quite good agreement with the well-known Heskestad flame height correlation given in equation 21. However, the diameter of the fire is required to apply equation 21 so a simpler correlation based on $\dot{q}^{2/5}$ was chosen for its simplicity. Figure 11 shows the predicted results using the $\dot{q}^{2/5}$ correlation where the proportionality constant has been chosen to provide the most favourable correlation. For this set upholstered furniture, the proportionality constant equal 0.118 giving the following relationship for flame height:

$$h_f = 0.118\dot{q}^{2/5} \qquad \text{Eq. 22}$$

The dotted lines in Figure 11 show the range of ±25%. Although the agreement is less than ideal, it is considered to be good agreement considering the complexity of the problem and the simplicity of the analysis.

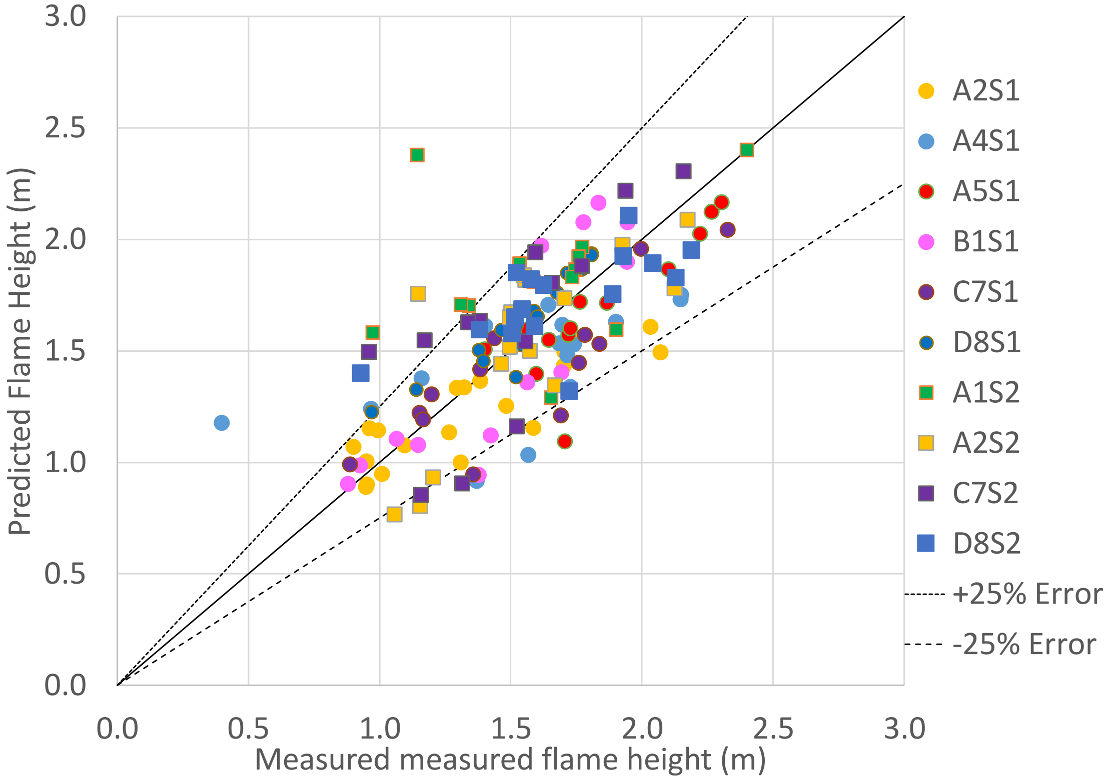


Figure 11 - Measured flame height versus predicted flame height

The advantage of this simple form of the equation is that it can be easily inverted to solve for the heat release rate from flame height observations. Inverting equation 22 gives the following relationship for the heat release rate:

$$\dot{q} = 8.5h_f^{5/2} \qquad \text{Eq. 23}$$

Equation 23 can now be evaluated using the flame height measurements from the data above to estimate the heat release rate given the flame height. However, the nature of the 5/2 power on the flame height means that small errors in the flame height, give large errors on the heat release rate. Figure 12 shows the predicted heat release rate using Eq. 23 compared to the measured heat release rate. Because any error in the flame height is amplified in the heat release rate prediction, the error bounds shown as the dashed lines are for +/-50%. Considering the complex nature of upholstered furniture, the results are considered favourable and more accurate than a simple expert judgement based on an experienced observer.

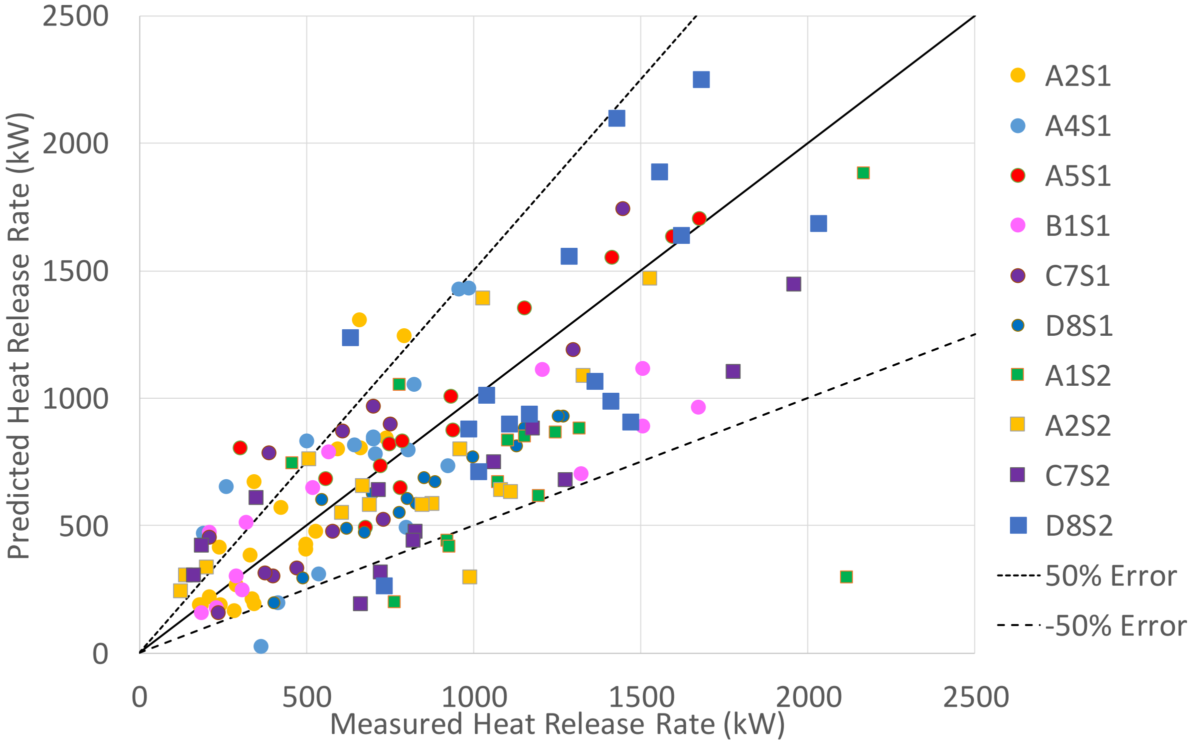


Figure 12 - Comparison of the predicted heat release rate versus the measured heat release rate.

This method could be used to estimate the energy release rate from a photo or video of a fire. To implement this technique, some form of scale from the image would be required. The dimension could be taken from the actual burning object, room height, or some other dimension of in the image. There is also the potential for parallax, an error induced when an object appears larger or smaller when observed from an angle. Such errors could be estimated, and corrected for, to improve the accuracy of the heat release rate estimates, but this is beyond the scope of this study.

3.3.7 Image Processing to Estimate Post-Flashover Energy Release Rate

When considering the energy release rate from a post-flashover fire, the energy can be divided into two components:

1) the energy released inside the compartment

2) the energy released outside the compartment.

In the case of Kawagoe's method, Equation 19 above, only estimates the energy released inside the compartment because it only accounts for the oxygen that enters the compartment to be burned. Yet for a ventilation limited compartment, there are typically large flames that are exhausted out of the opening because there is not enough oxygen in the room to burn the flammable gases within the compartment. It is, therefore, of interest to estimate the energy release rate within the compartment using Kawagoe's Equation 19 and the energy release rate of the flames out of the opening. Summing these 2 values give the total energy release rate within the compartment assuming that the external cladding is not ignited by the flames extending from the opening.

Rearranging Goble's Equations

There have been a few studies done on external flames from a compartment vent and these have been reviewed in the thesis by Goble[56]. Goble's carried out a series of experiments to measure the flame length from a post-flashover compartment with under ventilated fires with equivalence ratio ranging from $1.0 \leq \phi \leq 5.0$. Goble modified the original correlation by Lee et. al.[57] which identified the dependence of the flame height on the 2/3 and 2/5 power law of the heat release rate. In this study, the correlations were used with favourable predictions of the flame height as a function of the non-dimensional heat release rate, $\dot{q}*$ as shown below:

$$\dot{q}* < 1 \qquad z* = \frac{3.6\left(\dot{q}*\right)^{2/3}}{1.3} \qquad \text{Eq. 24}$$

$$\dot{q}* > 1 \qquad z* = \frac{3.7\left(\dot{q}*\right)^{2/5} - 0.1}{1.3} \qquad \text{Eq. 25}$$

Where:

$z*$ - non-dimensional flame height, $z* = \frac{z_{Flame}}{\ell_1}$

ℓ_1-non-dimensional window dimension, $\ell_1 = \left(A_O\sqrt{H_O}\right)^{2/5}$

A_O – area of the compartment opening
H_O – height of the compartment opening

$\dot{q}*$ - non-dimensional heat release rate, $\dot{q}* = \frac{\dot{q}_{External}}{\rho_\infty c_p T_\infty \ell_1 \sqrt{g}}$

$\dot{q}_{External}$ - heat release rate of the external flame from the opening

ρ_{∞} - density of air (1.2 kg/m^3)

c_p - specific heat of air (1.0 kJ/kg K)

T_{∞} - ambient air temperature (293 K)

Equation 23 can be dimensionalized by substituting in $\dot{q}*$ and $z*$, then rearranging to solve for $\dot{q}_{External}$ to get the following relationship:

$$\text{For} \quad \frac{\dot{q}_{External}}{A_O\sqrt{H_O}} \leq 1100 \qquad \dot{q}_{External} = 240\left(A_O\sqrt{H_O}\right)^{2/5} z_{flame}^{3/2} \qquad \text{Eq. 26}$$

Equation 24 is slightly more algebraically complicated with the 0.1 term and the rearranged equation becomes algebraically "messy". However, if the 0.1 term Equation 25 is ignored and the 3.7 is changed to 3.6 to maintain continuity at z_{fl}=1, then the equation becomes much easier to be applied for analysing video images of flame ejected from the window of a postflashover fire. Thus equation 25 can be simplified into:

$$z* = \frac{3.6\left(\dot{q}*\right)^{2/5}}{1.3} \qquad \text{Eq. 27}$$

Equation 27 is plotted in Figure 13 as the solid line compared to the original correlation of Eq. 25 as the dashed line. The results show minor impact of ignoring the modification to Equation 25. Then equation 27, in the dimensional form, becomes:

$$\text{For} \quad \frac{\dot{q}_{External}}{A_O\sqrt{H_O}} > 1100 \qquad \dot{q}_{External} = 86 z_{Flame}^{5/2} \qquad \text{Eq. 28}$$

Thus Equations 25 & 27 can be used to estimate the heat release rate.

At the time this article was written, the idea of estimating the heat release rate from a video image of the flame is considered conceptual. The challenge of using this technique is the large uncertainty caused by the power (3/2 and 5/2) on the z_{flame} depending on the size of the external flame.

The following analysis uses images from the FSRI to demonstrates the application of this method but is insufficient to prove the concept to any scientific certainty. The experiments were part of a FSRI project and not conducted as part of this research. The video was made available for this analysis and is used as an exemplar application. Because of the size of the fire relative to the laboratory, the entire flame was not able to be captured in the video frame which greatly limits the accuracy.

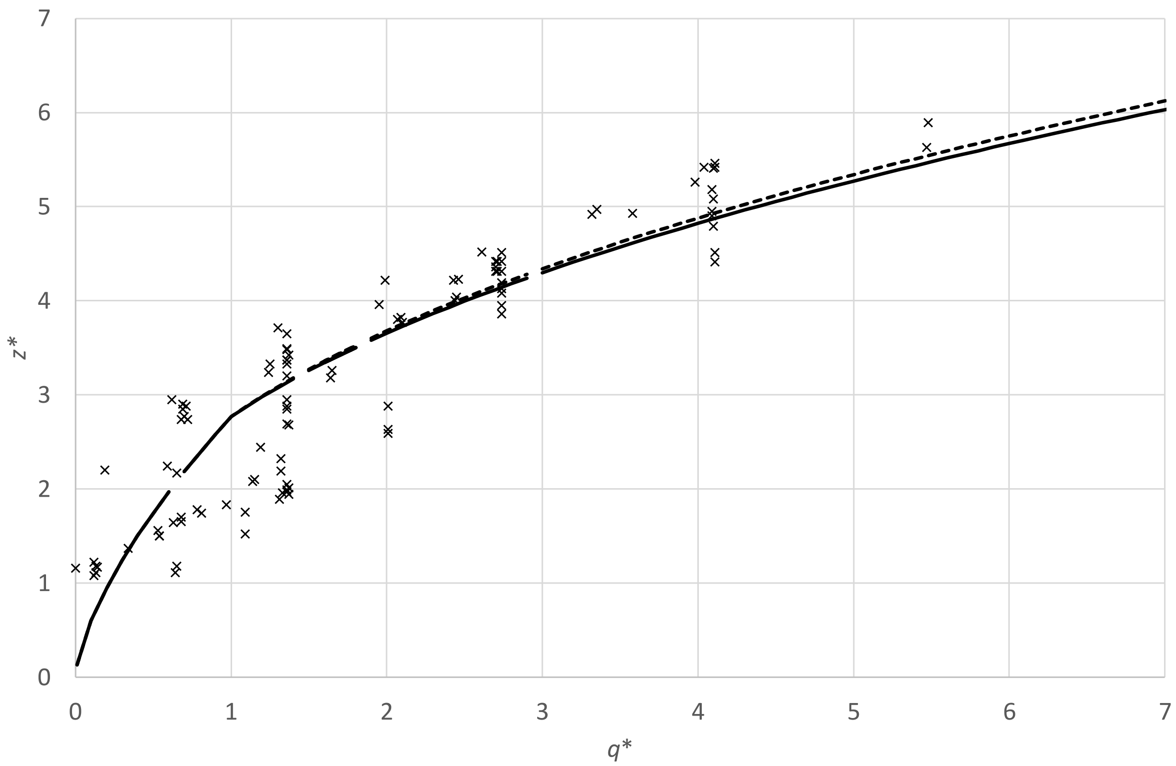


Figure 13 - Non-dimensional flame height versus non-dimensional heat release rate comparing modified flame height relationship with the original Delichatsios equation.

Video Footage Analysis - The experiment was a fully furnished compartment with an open door. (0.8m wide by 2.0m high). The image processing used the technique of Stratton[58] to analyse video images manually. Automated processing could be developed to analyse the videos and has been used by others.[56] Automated processing would allow for faster and potentially more accurate processing but requires significantly more setup time. In this report, it is a proof of concept and not a specific research project on predicting heat release rate form vented flames, so the manual analysis was used here. The available data is very limited and the videos available were not framed for this study, therefore, the results are only considered indicative at this time.

The flame height was measured visually on a frame by frame basis. To do this, the video was altered using video processing software so that there were ten frames per second. A square grid was also overlaid on the video footage, as shown below in Figure 14 .

Figure 14 - Video image of the flame compared to the same image with the analysis mesh over laid on the video image.

In order to determine the flame height, a known dimension must be taken from the video image. If the image moves then flame must be rescaled to adjust for the new camera location, In this case, the width of the door was known (0.8m), the size of a square were then calibrated for each frame of the footage and then used to determine the flame height. The width of the door had to be measured for each frame due to some shaking in the footage. Once the flame height was measured for each frame of the footage, the flame height was averaged over 1 second periods.

Results - Figure 15 shows the estimated heat release video footage along with selected images taken from the video for the reader to gain their perspective for the flame height. Below each of the images is the given the flame height as determined from the video analysis. For example, in the left most image the flame is 0.4m high and the right most image is 3.2 m high. Also included for each image, is the error bar showing the estimated error in the heat release rate which is a strong function of the measured flame height as discussed above. The y-axis gives the heat release rate and the x-axis is the time. The time scale is set to zero when the flames exit the compartment door, not the ignition time. The energy released within the postflashover compartment is estimated ventilation limited heat release rate based on Kawagoe, Equation 19 above. For the 0.8m wide and 2m high door, gives a ventilation limited value for 3400kW. The ventilation limited value is shown as the heat release rate at times less than zero in Figure 15. Note that the y axis starts at 3000kW to emphasise the heat release rate from the external flaming. The total heat release rate is the sum of the heat release rate in the compartment plus the heat release rate from any external flame. The maximum estimated heat release rate is approximately 5300kW. The error bars show the uncertainty in the estimated heat release rate when there is a 20% error in the measured flame height. The uncertainty is estimated based on the difficulty in measuring the flame height.

Discussion - The 5300 kW maximum, represents a 50% increase in the ventilation limited value which is within the expected range of 30 to 100% increase over the ventilation limited value. Because of the fuel in the compartment was mostly synthetic, primarily upholstered furniture and carpet, the value is lower than might be expected. However, in the video images included in Figure 15, clearly in the later images, the flame extends beyond the frame and therefore is not considered to be accurate. Unfortunately, the heat release rate was not available to compare with this data. In addition, the physical constraints of the lab prevented the video camera from being placed far enough away to capture the entire external flame.

Conclusion – Estimating the heat release rate from an external flame from external video observations is considered practical option. However, due to the physics of the problem, the method has a high degree of uncertainty because of the 3/2 to 5/2 power dependence on the flame height measurements. Before this method can be considered for practical application, a specific research project focusing on estimating the heat release rate from external flames is required to assess this methodology and to more accurately assess the uncertainty of the method.

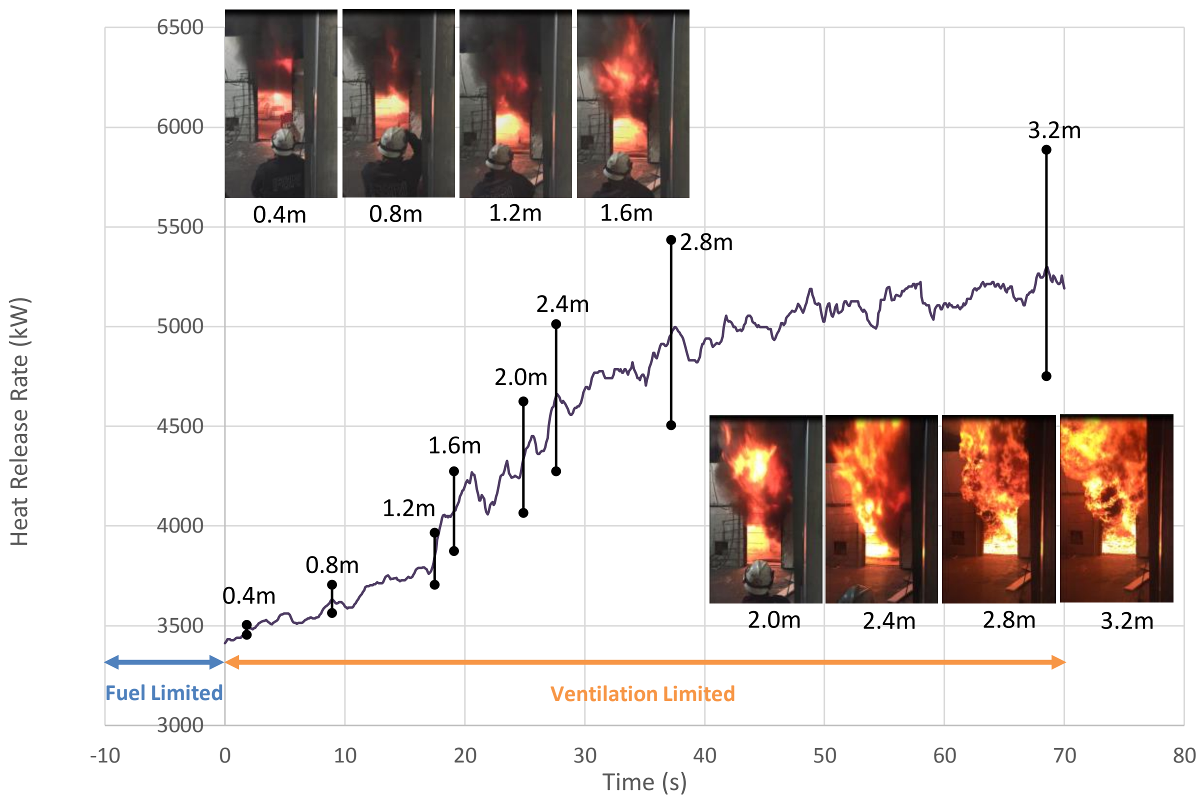


Figure 15 - Estimated heat release rate history for the ventilation limited burning phase including the error bars and flame height images.

4. CONCLUSIONS

This report reviews the international methodologies used to estimate the required fire flow rates the building fires. The result of this review indicate that most methods are derived from statistical information or expert judgement rather than fire dynamic principles. The review also demonstrates that there is no widespread agreement among the different methods and that results can vary widely.

This report also reviews the applications of fire dynamic principles to estimate the heat release rate for building fires that could be used to compare with the water flow required to extinguish a fire from actual fire incidents. Three different orders of magnitudes of analysis are outlined in the report. The zero-order analysis relies on the NFIRS data (both existing and future data) for the building/room of origin data and constant heat release rate per unit area (HRRPUA) for a building fire to estimate the heat release rate. This method relies more on the NFIRS data than fire dynamics and is considered to be quite crude and is not seen as an improvement to the current practice to PAS4509.

The first order analysis relies on the observations of the occupant and firefighter by trained investigators to estimate fire growth rate. The method also requires at least one HRRPUA to convert the growth rate from observations into a heat release rate. It is based on previous research by Holborn et al[32] and would provide useful information. The main disadvantage to this method is the relatively few fire events that have sufficient witness observations to be analysed.

The second order analysis applies currently available fire dynamic principles to estimate the heat release rate from fires. Typically, the data that may be available for such analysis are the damage patterns from the fire scene and video observations. Unfortunately, there have been few studies that have attempted to use damage patterns or videos to estimate heat release rate from fires. In addition, these methods come with a high degree of uncertainty because of the power law functions that come from the fundamental physics involved. Unfortunately, these methods have not been well researched to quantify the uncertainty and therefore are not considered to be reliable at this time. Future research may change this conclusion once the uncertainty has been better quantified.

In order estimate the heat release rate from fires, the most appropriate method at the time this report was written, is considered by the author to be the application of expert judgment to estimate heat release rate per unit area (HRRPUA) approach with more detailed fire investigation data and specially trained fire investigators or fire engineers. In the case of post flashover fires, equation 19 may also be applied. Not all of the information outlined in section 3.3.1 would be required but the better the documentation, the better results would be. Eyewitness accounts of the fire by both the public and firefighters would also be helpful in understanding the evolution of the fire. Details regarding the specific fuels consumed as well as the fuel available would be necessary. In addition to the more detailed investigation documentation, comprehensive tables of the HRRPUA from the literature would need to be developed. The limitation of the previous studies using this method has been:

1. General use of the HRRPUA values
2. Poor estimates of the area involved in the fire as either categories or gross areas.
3. Assuming complete combustion of the fuel.
4. No estimate of the heat release rate form ventilation limited values.

It is also considered advantageous to collect and analyse video and image data to apply the other techniques outlined in the 2nd order analysis section for comparison with the results HRRPUA results.

5. REFERENCES

---

[1] Standards New Zealand. (2008). SNZ PAS 4509:2008 New Zealand Fire Service Firefighting Water Supplies Code of Practice.

[2] Davis, Simon, Fire Fighting Water: A Review of Fire Fighting Water Requirements a New Zealand Perspective, Fire Engineering Research Report 00/3, University of Canterbury, March 2003.

[3] Benfer, ME and Scheffey, JL, "Evaluation of Fire Flow Methodologies", The Fire Protection Research Foundation, January 2014.

[4] Grimwood, P and Sanderson, I A, The County/Metro research into fire-fighting suppressive capacity and the impact on building fire damage at 45000 UK building fires, 2009–2012, *Fire Safety Journal,* **71**, 238-247, 2015, http://dx.doi.org/10.1016/j.firesaf.2014.11.027.

[5] ISO Properties. (2008). Guide for Determination of Needed Fire Flow. Retrieved from http://www.ecs.umass.edu/cee/reckhow/courses/371/Documents/Needed%20Fire%20Flow%20Guide%202008.pdf

[6] Myburgh, E. (2012). Evaluating Methods for Fire Protection and Related Fire Risk Categories in Rural Towns of the Western Cape, South Africa. University of Stellenbosch. Retrieved from http://scholar.sun.ac.za/bitstream/handle/10019.1/20066/myburgh_evaluating_2012.pdf?sequence=1&isAllowed=y

[7] Torvi, D., Hadjisophocleous, G., Guenther, M. B., & Thomas, G. (2001). Estimating water requirements for firefighting operations using FIERAsystem. Fire Technology. https://doi.org/10.1023/A:1012487619577

[8] International Fire Codes. (2018). 2018 International Fire Codes - APPENDIX B FIRE-FLOW REQUIREMENTS FOR BUILDINGS. Retrived from https://codes.iccsafe.org/content/IFC2018/APPENDIX-B-FIRE-FLOW-REQUIREMENTS-FOR-BUILDINGS

[9] NFPA 1142, Water Supplies for Suburban and Rural Fire Fighting, 2012 Edition, National Fire Protection Association, Quincy, MA, 2011.

[10] International Wildland-Urban Interface Code 2012, International Code Council, Illinois, 2011.

[11] Ontario Building Code 1997, July 1, 2005 Update, Ministry of Municipal Affairs and Housing, Ontario, Canada, 2005

[12] D9 Technical Document, External Fire Control – Determination of Water Supply, INESC-FFSACNPP Enterprise, France, 2001.

[13] National guidance document on the provision of water for fire fighting (3rd edition; Jan 2007). Water UK. (2007). Retrieved from https://www.water.org.uk/publications/water-industry-guidance/national-guidance-document-provision-water-fire-fighting-3rd

[14] Royer, K. (1995). Iowa Rate of Flow Formula for Fire Control. FireEngineering. Retrieved from https://www.fireengineering.com/articles/print/volume-148/issue-9/features/iowa-rate-of-flow-formula-for-fire-control.html%0A

[15] Thomas, P.H., "Use of Water in the Extinction of Large Fires," The Institution of Fire Engineers Quarterly (19), no 35/1959, pp. 130-132.

[16] Baldwin, R., "Use of water in the extinction of fires by brigades," The Institution of Fire Engineers Quarterly (31), no 82/1972, pp. 163-168.

[17] Särdqvist, S., "An Engineering Approach to Fire-Fighting Tactics," Dept. of Fire Safety Engineering, Lund University, ISSN 1102-8246, ISRN LUTVDG/TVBB-1014-SE, Sweden, 1996

[18] Wenzel, L.J., "Water Supply Requirements for Public Supply Systems," *NFPA Handbook, 20th Edition,* Section 15, Chapter 2, Quincy, MA.

[19] Myburgh, E. (2012). Evaluating Methods for Fire Protection and Related Fire Risk Categories in Rural Towns of the Western Cape, South Africa. University of Stellenbosch. Retrieved from http://scholar.sun.ac.za/bitstream/handle/10019.1/20066/myburgh_evaluating_2012.pdf?sequence=1&isAllowed=y

[20] Hadjisophocleous, G. V., & Richardson, J. K. (2005). Water flow demands for firefighting. Fire Technology. https://doi.org/10.1007/s10694-005-1269-6

[21] Wieder, M.A., Fire Service Hydraulics and Water Supply, Fire Protection Publications, Oklahoma, 2005

[22] Grimwood, P. (2005). Fire-fighting Flow-rate [Barnett (NZ) – Grimwood (UK) Formulae]. Retrieved from https://firenotes.ca/download/Flow_Rates_for_Firefighting.pdf

[23] Grimwood, P. (2014). In Full Flow. Fire & Risk Management. Retrieved from http://cfbt-be.com/images/teksten/In full flow grimwood.pdf

[24] Barnett, C. (2007). *SFPE (NZ) Technical Publication - TP 2007/1 Comparison of 11 Methods for Determining Water Used for Fire Fighting*, Society of Fire Protection Engineers (New Zealand), 2007.

[25] Fire Underwriters Survey, 2009. Water supply for public fire protection. Canada.

[26] Chang, C. H., & Huang, H. C. (2005). A water requirements estimation model for fire suppression: A study based on integrated uncertainty analysis. *Fire Technology*. https://doi.org/10.1007/s10694-005-4627-5

[27] McLean, J. D. (2013). Innovative Approach to Fire Flow Assessment for the Christchurch Water Supply Rezoning. Christchurch. Retrieved from https://www.waternz.org.nz/Article?Action=View&Article_id=294

[28] "SFPE (NZ) Technical Publication - TP 2004/1, Calculation Methods for Water Flows Used For Fire Fighting Purposes," Society of Fire Protection Engineers (New Zealand), 2004.

[29] "SFPE (NZ) Technical Publication - TP 2005/2, Calculation Methods for Storage Water Used for Fire Fighting Purposes," Society of Fire Protection Engineers (New Zealand), 2005.

[30] Editor, A. H. B. (2001). Fire Engineering Design Guide. Journal of Chemical Information and Modeling. https://doi.org/http://hdl.handle.net/10092/11531.

[31] "SFPE (NZ) Technical Publication - TP 2007/1 Comparison of 11 Methods for Determining Water Used for Fire Fighting," Society of Fire Protection Engineers (New Zealand), 2007.

[32] Holborn, P G, Nolan, P F, and Golt, J, "An analysis of fire sizes, fire growth rates and times between events using data from fire investigations", *Fire Safety Journal*, **39**, 418-524, 2004.

[33] Alpert, R L, "Ceiling Jets", SFPE Handbook of Fire Protection Engineering, 5th edition, Chapter 14, 2016.

[34] Hadjisophocleous, G V and Mehaffey, J R, "Fire Scenarios", SFPE Handbook of Fire Protection Engineering, 5th edition, Chapter 34, 2016.

[35] Madrzykowski, D and Weinschenk, C, "Impact of Fixed Ventilation on Fire Damage Patterns in Full-Scale Structures", UL Firefighter Safety Research Institute Columbia, MD, USA, 2019. https://ulfirefightersafety.org/docs/Fire_Damage_Patterns_in_Full_Scale_Structures.pdf

[36] NFPA921 - Guide for Fire and Explosion Investigations, National Fire Protection Association, 2017.

[37] Hopkin, C, Spearpoint, M, Hopkin, D, "A Review of Design Values Adopted for Heat Release Rate Per Unit Area" *Fire Technology*, **55**, 1599-1618, 2019. https://doi.org/10.1007/s10694-019-00834-8

[38] Babrauskas, V, Heat Release Rates, *SFPE Handbook of Fire Protection Engineering*, 5th edition, Chapter 26, 2016.

[39] K. Kawagoe, "Fire Behaviour in Rooms", Report of the Building Research Institute, No.27, Building Research Institute, Ministry of Construction, Japan (1958).

[40] Rockett, J A "Fire Induced Gas Flow in an Enclosure," *Combustion Science and Technology,* 12 165-175, 1976.

[41] Karlsson, B, and Quintiere, J G, *Enclosure Fire Dynamics,* CRC Press, Chapter 4, 2000.

[42] Rethoret H, *Fire Investigations*, Recording and Statistical Corporation, Canada, 1945.

[43] Beyler C, Analysis of the Fire Investigation Methods and Procedures Used in the Criminal Arson Cases Against Ernest Ray Willis and Cameron Todd Willingham. Hughes Associates, Maryland (USA), 2009.

[44] Gorbett, G E, Meacham, B J, Wood, C B, and Dembsey, N A, "Use of damage in fire investigation: a review of fire patterns analysis, research and future direction", *Fire Science Reviews,* 2015. DOI 10.1186/s40038-015-0008-4.

[45] Barnott A, Hardman R, Hoff, N, "An Improved Method for Measuring Depth of Calcination in Fire investigations". Poster presented at the International Association of Arson Investigators Annual Training Conference, Florida, USA, 2013.

[46] A.J. Wolfe. "Analysis and Application of Calcination Depth Probing Tool and Technique", Proceedings of the International Symposium on Fire Investigation Science and Technology,691–701, 2014.

[47] Babrauskas, V, "Wood Char Depth: Interpretation in Fire Investigations", Presented at International Symposium on Fire Investigation, Fire Service College, Moreton-in-Marsh, United Kingdom, 28 June 2004

[48] Babrauskas, V., "Charring rate of wood as a tool for fire investigations", *Fire Safety Journal",* **40**, 528-554, 2005.

[49] Madrzykowski, D, "Repeatability of Preflashover Fire Patterns on Gypsum Wallboard", PhD Thesis, University of Canterbury,2017.

[50] Heskestad, G, "Fire Plumes, Flame Height, and Air Entrainment", *SFPE Handbook of Fire Protection Engineering*, 5th edition, Chapter 13, 2016.

[51] Beyler, C L, "Fire Plumes and Ceiling Jets," *Fire Safety Journal*, **11**, 53-75, 1986.

[52] Fleischmann, C M and Hill G R, *Burning Behaviour of Upholstered Furniture,* Interflam '04, Interscience Communications Co., London, 2004.

[53] Enright, P. A. and Fleischmann, C. M. "CBUF Model I, Applied to Exemplary New Zealand Furniture", Proceeding of the Sixth International Symposium on Fire Safety Science, 2000.

[54] Enright, P A, "Heat Release and The Combustion of Upholstered Furniture" PhD Thesis, University of Canterbury, 1999.

[55] Fleischmann, C M, "Predicting Radiative Heat Flux From Uphosltered Furniture Fires", International Congress - Combustion and Fire Dynamics, University of Cantabria, Santander, Spain, 2010.

[56] Goble, K. *Height of Flames Projecting from Compartment Openings*. Christchurch: University of Canterbury, 2007.

[57] Lee, Y P, Delichatsios, M A, Silcock, G W H, "Heat fluxes and flame heights in facades from fires in enclosures of varying geometry", Proceedings of the Combustion Institute, **31**, 2521–2528, 2007. https://doi.org/10.1016/j.proci.2006.08.033

[58] Stratton, B. (2005). *Determining Flame Height and Flame Pulsation Frequency and Estimating Heat Release Rate from 3D Flame Reconstruction.* Christchurch: University of Canterbury.