On the design fire for safety provision

Walter W. Yuen
Department of Mechanical & Environmental Engineering
University of California at Santa Barbara
California, USA

and

W.K. Chow
Department of Building Services Engineering
The Hong Kong Polytechnic University
Hong Kong, China

June, 2002

Abstract

A method is proposed for determining the design fire for a typical building use. This is based on the earlier approach by Morgan and was widely used in many places. In contrast to the earlier work, however, uncertainties in fire statistics and fire physics are included in the present work. The Monte Carlo method is used to estimate these uncertainties. The approach is recommended for the Authority to work out a design fire.

1. Introduction

In the determination of the fire safety provision for buildings, there is a need to specify a "design fire". This is an important issue in the development of engineering performance-based fire codes (EPBFC) [e.g. 1-4]. In the prescriptive code on smoke management system (SMS), the specification of a design fire is also required [5-7]. In essence, the key question [e.g. 8] is:

How big is the fire?

The size of a fire is related to the heat release rate. To determine a design fire, a database on heat release rate should thus be developed [9]. The size of the fire and its heat release rate is the first and most important element among the following list of parameters commonly used to characterize an unwanted fire [8,10]:

- An indication of the size of the fire.
- The rate of fire growth, and consequently the release of smoke and toxic gases.
- The time available for escape or fire suppression.
- The type of suppressive action that is likely to be effective.
- Other attributes that define the fire hazard.
- Whether flashover would occur.

Designers have used different values of heat release rate for different type of buildings in the past. Typical values used in local projects are [11]:

- Airport and train terminal hall: up to 7 MW
- Shopping mall: 5 MW
- Atrium: up to 7 MW
- Train compartment: 1 MW

Even with the above prescriptive value, however, designers must still exercise "engineering judgment" for a specific situation. For example, in the sizing of natural vents for static smoke extraction system, the heat release rate for the design fire cannot be too high. If 7 MW is chosen as the design value, an accidental fire with a much smaller heat release rate can push cool air, instead of smoke, down from the vent. On the other hand, the heat release rate of the design fire in a mechanical ventilation system (dynamic smoke extraction) cannot be too small. A fire with a much higher heat release rate can lead to a smoke production rate higher than the operating flow rate of the fan. In general, the heat release rate of a design fire must thus be specified carefully.

Currently, apart from developing a database based on full-scale burning tests [e.g. 3,9,13-15], the practical method developed by Morgan and Hansell [12] can be used for determining the heat release rate for a design fire. This method had been widely used in many places, especially in areas that are under British Administrations (either currently or previously) such as Hong Kong.

Based partially on the UK Fires Statistics Data Base and some limited consideration of fire physics, the approach determines, for a building with a given ventilation area and geometry, a heat release rate, Q, such that the cumulative probability of fire with a "higher" damage occurred in the building is less than x. Mathematically, the heat release rate is given by:

$$Q = F\,(A_w, H, x)$$

where A_w and H are the area and height of the ventilation, x is the desire cumulative probability.

While the current approach is useful in generating a quantitative estimate of the heat release rate, particularly in relation to a cumulative probability of damage, it can be improved by including the uncertainty in the statistical data and the uncertainty in fire physics. The objective of the present work is to show that a Monte Carlo simulation [16] can be used to develop a probabilistic approach to determine the heat release rate for a design fire. This approach allows the inclusion of the uncertainty of both the Fire Statistics and fire physics. Within the probabilistic framework, both the heat release rate and its associated uncertainty can be determined for a specific cumulative probability of damage.

2. The Design Method by Morgan and Hansell [12]

This process of determining the design fire [12] is done into 2 steps.

- First, the 1978-79 U.K. Fire Statistics Data Base, as shown in Figure 1, is used to find a relation between a cumulative probability x and the fire damage area, A_{FD}, i.e.,

  $A_{FD} = f_1(x)$ = the fire damage area at which the cumulative probability that a fire will have a fire damage area greater than or equal to A_{FD} is x.

  Specifically, the reported fire data are presented as discrete probability distribution and cumulative probability distribution in Figures 2 and 3. By taking a linear interpolation of the lower limit of the cumulative probability distribution, $f_1(x)$ is generated and shown in Figure 4.

- Once x (and therefore A_{FD}) is chosen, fire physics is then used to determine the appropriate heat release rate for a design fire

  $Q = f_2\,(A_w, H, A_{FD})$

The deterministic and/or probabilistic behavior of the two functions, f_1 and f_2, will thus affect the validity of the selection of Q in meeting the design goal.

To determine Q, the "best" available correlations from fire physics at the time were used [12]. Specifically, the function $f_2(x)$ is represented by the block diagram shown in Figure 5. The equation used to determine whether a fire is fuel controlled or ventilation controlled is:

$$\begin{aligned} &\frac{A_w\sqrt{H}}{A_{FD}} > 0.317 \qquad \text{fuel-bed controlled} \\ &\frac{A_w\sqrt{H}}{A_{FD}} < 0.317 \qquad \text{ventilation controlled} \end{aligned} \tag{1}$$

For a ventilation controlled fire, the heat output is determined by:

$$Q_f = 456 C_s A_w \sqrt{H} \tag{2a}$$

where C_s is a correction factor used to account for the effect of sprinkler. Morgan and Hansell used a value of 0.5. For a fuel-bed controlled fire, the heat output is given by:

$$Q_f = 260\ C_h C_s A_{FD} \qquad (2b)$$

where C_h is a factor used to account for the heat loss to the compartment boundary. Morgan and Hansell recommended a value of 1/3 for C_h. Equations (1), (2a) and (2b) were determined based on their "best" judgement on the validity of both the functional expressions and the associated constants for desgin purposes. There were no consideration of uncertainty of either the choice of the models or the associated constants.

For a particular set of ventilation parameter, equations (1), (2a) and (2b) will generate a functional relation between the design fire, Q_f, and the fire damage area, A_{FD}. A numerical example (with H = 3 m, $A_w = 9\ m^2$) of the relation is shown in Figure 6. Note that the fire damge area is a monotically increasing function of the design fire only in the region of a fuel-bed controlled fire. At the transition to a ventilation controlled fire, the design fire takes a step change to the value given by equation (2a) and become insensitive to the fire damage area. This model is thus not quantitatively useful for design purpose after the transition to a ventilation controlled fire.

In essense, Figures (4) and (6) contain all the basic information needed for the design method of Morgan and Hansell [12]. For a design objective of x = 0.1 (i.e. the selection of a design fire accounting for 90% of the fire damage cases), for example, the utilization of $f_1(x)$ in figure 4 leads to a fire damage area of 11 m^2 and 47 m^2 for the sprinkler and no-sprinklered case respectively. From Figure 6, a design fire of 4.1 MW for an unsprinklered office and 0.48 MW for a sprinklered office is determined.

To illustrate the general behavior of the design process, the design fire estimated by the flow diagram in Figure 5 for an office with ventilation parameters of $A_w = 9\ m^2$ and H = 3 m is tabulated and shown in Figure 7. Results show that the transition from a fuel-bed controlled fire to a ventilation controlled fire occurs at x = 0.05 for the sprinklered case and 0.1 for the unsprinklered case. Eventhough a design fire value is assumed for the ventilation case, it has a limited design application. For example, the utlization of a design fire value of 7.1 MW (the value for a ventilation fire) for the unsprinklered case can only assure that the design accounts for 90% of the expected fire (x = 0.1, assuming that $f_1(x)$ is totally valid). The model cannot generate a design fire value for a design goal of x < 0.1. This illustrates the importance of equation (1). Its applicability to the specific offices/buildings under consideration must be carefully assessed. The relative accuracy of equations (2a) and (2b) must also be considered to assure the reliability of the predicted design fire.

3. Improvement of the Design Method

Even with a determinstic approach, the uncertainty in the selection of a design fire is well known. Indeed, systematic and rigorous assessment of the uncertainty are expected by the Authority in approving design fire. The lack of a systematic approach, however, has led to arbitrary adjustment of the design value such as adding of a "safety" factor based on "expert" opinion. Additional risk might thus be introduced into the design.

There are uncertainties associated both with the determination of the fire damage area from the UK fire statistic data base, $f_1(x)$, and the equations used to describe the relevant fire physics (Figure 4, equations (1), (2a) and (2b) and Figure 6). Since data base is never complete and is subjected to update from new data, the interpretation of the data base must be done statistically with appropriate conservatism. Similarly, the understanding of various important mechanisms in fire physics can also be uncertain as most of them relied on experimental data. Identifying those uncertainties and their effect on the predicted design are extremely important in convincing the Authority on the validity of the design, particularly to those without good understanding of advanced fire dynamics.

In the following sections, an approach to address these uncertainties is demonstrated. The fundamental philosophy of the approach is to identify uncertainty in each step of the design process (interpretation of data, utilization of a mathematical correlation to describe a particular physical process, etc.) and to provide a statistical characterization of its effect on the design. As an illustration, a Monte Carlo approach [16] will be used to provide a numerical example. Specifically, the approach will yield a best-estimated value of the design parameter (for example, the design fire, Q_f) correspond to a specific design objective (x, the cumulative probability to have a larger FDA). Since the uncertainty of the model is identified, the current approach will also provide an estimate of the statistical uncertainty of the design. This statistical information can be useful for other decisions such as system improvement and the identification of research areas to eliminate uncertainties in physical models.

The uncertainty of $f_1(x)$

Even if the uncertainty of the reported fire damage area can be ignored (they are difficult to assess), there are inherent uncertainty in the relation between the cumulative probability x and the fire damage area since data are reported over discrete ranges of fire damage area (for example, 24 fires were reported with a range of fire damaged area between 151 and 200 m^2 for unsprinklered office). This leads to the "step function" behavior as shown in Figure 3. In view of the possible transition from a fuel-bed controlled fire to a ventillation controlled fire can occur over a small change in the fire-damage area at some critical value of x (assuming the modelling of fire physics using figure 4, equations (1), (2a) and (2b) is accurate), the approach of Morgan and Hansell can thus be highly "unconservative" and can underpredict the design fire.

Statistically, an approach which can account for the uncertainty is to consider the "upper" and "lower" bound of the cumulative probability function as shown in Figure 8. Using Figure 4, equations (1), (2a) and (2b) (and Figure 5), the corresponding bounding value for the fire damage area and design fire (again for the case with $A_w = 9\ m^2$, $H = 3$ m) is shown in Figure 9.

It is interesting to note that the spread between the upper and lower bound of the design fire, for a particular design objective x, can be quite large due to the transition from a fuel-bed controlled fire to a ventillation controlled fire. In Figure 9, the average design fire is calculated assuming that the fire damage area has a uniform probablity to have any value between the lower and upper bound. Note that the average design fire is not the average of the upper and lower limit of the design fire. This is due to the highly nonlinear relation between fire damage area and design fire.

While a great deal of the uncertainty in the predicted design fire can be attributed to the uncertainty of the model used in the determination of the design fire (Figure 4, equations (1), (2a) and (2b)), the effect of the uncertainty in the selection of the fire damage area for design is clearly significant. The effect is particularly important in region where the transition from a fuel-bed controlled fire to ventilation-controlled fire might occur. Since data for damage area for reported fire will always be limited, the assessment of uncertainty will always be important if such data is used as a basis for the selection of design fire.

<u>The uncertainty in fire physics</u>

Even with the significant amount of research which have been conducted on the many physical phenomena which are important for the understanding of fire, significant amount of uncertainty still exist and will continue to exist in the modeling of fire in practical situations. The appropriate consideration of these uncertainties is thus extremely important for any design process involving fire.

The current discussion will focus only the relations and phenomena considered by Morgan and Hansell [12] in their approach in selecting a design fire. While this limits the scope of the present discussion, it is sufficient for the current objective, which is to illustrate the appropriate consideration of uncertainty in fire design. Expansion to account for other phenomena is quite straightforward and can be considered in the future.

- Correlation for transition between fuel-bed controlled and ventilation controlled fire

  As shown by results in Figures 6 and 8, the transition between a fuel-bed controlled fire to a ventilation-controlled fire is extremely important in the prediction of the design fire. Physically, however, this transition depends on a large number of factors such as fuel type and room geometry. A typical representation [17] of the transition data for different fuel is shown in Figure 10. Equation (1) is clearly not an adequate representation of the actual observation. A more appropriate correlation would be

$$\begin{aligned} &\rho_a g^{1/2} \frac{A_w H^{1/2}}{A_{FD}} > C_t + \delta \qquad \text{fuel-bed controlled} \\ &\rho_a g^{1/2} \frac{A_w H^{1/2}}{A_{FD}} < C_t \qquad \text{ventilation controlled} \end{aligned} \tag{3}$$

  The identification of two transition constants, C_t and δ, is to account for the behavior that the transition not only occur at different value of the transition constant (depending on materials and other fire parameters), it also occurs smoothly over a range of the dimensionless parameter $\rho_a g^{1/2}(A_w H^{1/2} / A_{FD})$. In general, the value of the transitional constant, C_t and δ, their ranges and the relative probabilistic distribution within the range, can be determined by the designer based on the specifics of an application and data such as those [e.g. 17] shown in Figure 10. For example, if materials in the office/building are limited to a certain type, C_t and δ can be selected based only on combustion data for the specific materials. If no restriction on materials can be made, a reasonable approach will be to assume that C_t and δ are bounded by a minimum and maximum value with some probability distribution of having any intermediate value. Mathematically, using only data from Figure 10, one can assume the following discrete probability distribution for C_t:

$$P(C_t) = \begin{cases} 1 & \text{for} \quad 0.3 < C_t < 5.0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

  and δ can be assumed to a constant with a value of about 0.1.

Note that the selection of the bounding values and the exact probabilistic distribution is part of the decisions made by the designer based on the "best" information available. Indeed, equation (1) can be considered as a special case of equation (4) in which the probabilistic distribution is assumed to be a "delta" function at $C_t = 1.19$ and $\delta = 0$.

- Correlation for the heat output from a ventilation controlled fire

The development of equation (2a) is based on the assumption that the heat output from a ventilation-controlled fire can be written as

$$Q_f = mC_p\theta \tag{5}$$

where m is the mass flow rate of the gas, C_p the specific heat and θ the temperature rise of the hot gases above the ambient. To obtain equation (2a), the following correlation for mass flow rate (based on experimental data for wood crib fires) is utilized,

$$m = 0.5A_w\sqrt{H} \tag{6}$$

together with the assumption of $C_p = 1.0$ kJ/kg-K and a temperature rise of 1200 K.

The utilization of wood crib fires data for the determination of the mass flow rate is clearly too restrictive. Indeed, the data for polyethylene shown in Figure 9, for example, show a higher burning rate than wood in the ventilation-controlled regime. To account for the presence of different fuel, equation (6) is replaced with a more general correlation

$$m = C_vA_w\sqrt{H} \tag{7}$$

and C_v is given by the following discrete probability distribution

$$P(C_v) = \begin{cases} 1 & \text{for} \quad 0.4 < C_v < 0.6 \\ \\ 0 & \quad\quad \text{otherwise} \end{cases} \tag{8}$$

Equation (8) assumes that there is a 20% variation of the constant C_v is around the wood crib value (and also theoretical value) of 0.5. For simplicity, no statistical variation of the temperature rise is implemented.

- Correlation for the heat output from a fuel-bed controlled fire

Equation (2b) is based on the burning rate data [12] presented Figure 11. Assuming a fire load per unit floor area of 57 kg/m^3 and using the wood cribs curve, a burning rate per unit area was determined from Figure 9 to be 14.4×10^3 kg/m^2/s. Taking the calorific value of wood to be 18 MJ/kg, the ratio of heat output to fuel area is determined to be 260 kW/m^2, which is the basis of equation (2b). Since there is uncertainty associated with the fire load per unit area and also with the form of the fuel, the ratio of heat output to the fire damage area has significant uncertainty. Taking the limit between the curves with normal and high ratio of fuel surface to fuel mass and assuming the same fire load per unit floor area of 57 kg/m^3, the burning rate per unit area will vary between 5 and 20×10^3 kg/m^2/s. Assuming that the calorific value of fuel remains approximately the same at 18 MJ/kg, equation (2b) is replaced by the following expression.

$$Q_f = C_{fb} C_h C_s A_{FD} \tag{9}$$

where

$$P(C_{fb}) = \begin{cases} 1 & \text{for} \quad 90 < C_{fb} < 360 \\ 0 & \quad\text{otherwise} \end{cases} \tag{10}$$

- Effect of sprinkler and convective heat loss

Morgan and Hansell estimated that between 40% to 60% of the heat carried by the gas would be lost to the sprinkler spray. They use a value of 0.5 for C_s for their deterministic model. In the present illustration, C_s will be assumed to have the following discrete probability distribution

$$P(C_s) = \begin{cases} 1 & \text{for} \quad 0.4 < C_s < 0.6 \\ 0 & \quad\text{otherwise} \end{cases} \tag{11}$$

For fuel-bed controlled fire, two-third of the heat generated by the fire is assumed to be lost to the compartment boundary. This lead to a value of 1/3 for the constant C_h. No statistical variation is assumed for C_h in the present consideration since its effect can be partially included in the statistical variation of C_s.

4. Prediction by the Monte Carlo Method

Using the Monte Carlo method, a modified relation between the design fire and fire damage area, including the effect of uncertainty, can be generated to replace figure 5. Specifically, for a given value of the design fire, the probabilistic distributions as represented by equations (4), (8), (10) and (11) can be simulated by random sampling. Numerical results for the simulation of the 4 parameters with 50,000 samples are shown in Figure 12. The probability distribution of A_{FB} with Q = 800 kW is shown in Figure 13.

The points labeled 90% and 10% are values at which the cumulative probability of the fire damages area below those values are 90% and 10% respectively. Statistically, 80% of the expected values of fire damage area are bounded between these two figures. For a building with the venting dimension of A_w = 9 m^2 and H = 3 m, the fire damge area for different design fire generated by the Monte Carlo method, together with results generated from Morgan's deterministic model (Figure 7) are shown in Figure 14.

As expected, the model of Morgan and Hansell is bounded by the 10% and 90% lines of the current model since it is essentially a special case of the current statistical model. It is interesting to note that relative to the 90% line, the Morgan's model is too conservative. For a design objective of 0.1 and a fire damage area of 11 m^2 and 47 m^2 for the sprinkler and no-sprinklered case, the 90% line leads to a heat output of 0.2 MW and 3.5 MW for the two cases respectively (in contrast to the Morgan's approach which would lead to values of 0.48 and 4.1 MW).

Using a deterministic relation for $f_l(x)$ as shown in Figure 4, together with the 90% curves shown in Figure 12, the design fires for different design objective, x, can be calculated. For the same ventilation setting as that in Figure 7, numerical data are generated and they are shown in Figure 15 (along with results from Figure 7 as a comparison). It is clear that the Monte Carlo results will lead a reduction in the design fire while maintaining a significant level of conservatism.

5. Conclusion

The approach by Morgan and Hansell [12] in a design fire to meet particular design criteria is generalized to account for both the uncertainty of the available data and the uncertainty in fire physics. A Monte Carlo approach [16] is shown to be effective in generating effective design accounting for the uncertainties.

References

1. G.V. Hadjisophocleous, N. Bénichou and A.S. Tamin "Literature review of performance-based codes and design environment" Journal of Fire Protection Engineering, Vol. 9, No. 1, pp. 12-40 (1998).
2. SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design of Buildings, Quincy, MA, Society of Fire Protection Engineers and National Fire Protection Association (2000).
3. British Standards Draft to Development DD 240, Fire safety engineering in buildings, Part 1, Guide to the application of fire safety engineering principles, British Standards Institution, London (1997).
4. CIBSE Guide E, Fire engineering, The Chartered Institution of Building Services Engineers (1997).
5. Guide for smoke management systems in malls, atria and large areas. NFPA 92B, National Fire Protection Association, Quincy, MA, USA (1995).
6. I.L.R. Schoonbaert, H.P. Morgan, B.K. Ghosh, G. Garrad, D.R. Pamlitschka and J-C De Smedt "Design methodologies for smoke and heat exhaust ventilation" BR368 Building Research Establishment, Garston, Watford, UK (1999).
7. J.H. Klote and J.A. Milke "Design of smoke management system" American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Ga, USA (1998).
8. R.D. Peacock, R.W. Bukowski, W.W. Jones, P.A. Reneke, V. Babrauskas and J.E. Brown "Fire safety of passenger trains: A review of current approaches and of new concepts" NIST Technical Note 1406, National Institution of Standards and Technology, Maryland, USA (1994).
9. Fire Protection Engineering Handbook, Society for Fire Protection Engineering, National Fire Protection Association, Ma, USA (2002).
10. C. Huggett "Estimation of rate of heat release by means of oxygen consumption measurement" Fire and Materials, Vol. 4, No. 2, p. 61-65 (1980).
11. W.K. Chow "Birth of the new subject: Fire safety engineering and review on the associated research activities" A Lecture to Beijing Polytechnic University, 17-22 May 2002, Beijing, China (2002).
12. H.P. Morgan and G.O. Hansell "Fire sizes and sprinkler effectiveness in offices – Implications for smoke control design" Fire Safety Journal, Vol. 8, p. 187-198 (1984/85).
13. G. Garrad and D.A. Smith "The characterisation of fires for design" Interflam'99, Proceedings of 8th International Fire Science & Engineering Conference, 29 June – 1 July, Edinburgh Conference Centre, Scotland, Vol. 1, p. 555-566 (1999).

14. B.K. Ghosh "Fires in real scenarios" International Symposium on Fire Science and Technology, New Trends of Fire Technology towards the 21st Century, November 12-14, 1997, Seoul Education & Culture Center, Seoul, Korea, organized by Korean Institute of Fire Science & Engineering.
15. Gigi C.H. Lui and W.K. Chow "A survey on heat release rate curves for burning items in a karaoke box" Journal of Applied Fire Science, Vol. 9, No. 4, p. 381-393 (2000).
16. "The Monte Carlo Method" International Series of Monographs in Pure and Applied Mathematics, Vol. 87 (1966), General Editors: Sneddon, I.N., Stark, M. and Ulam, S.
17. D. Drysdale "An introduction to fire dynamics" John Wiley & Sons – Chichester (1985).

WY20021dy

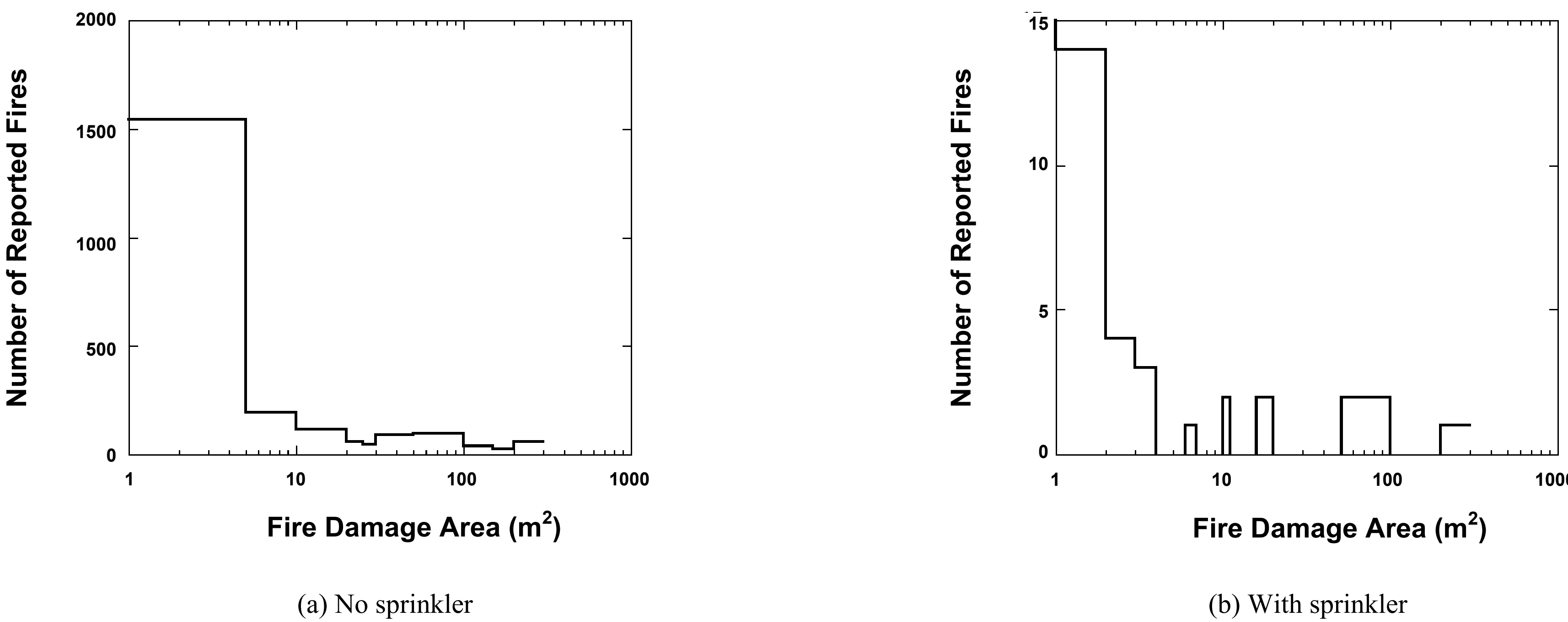
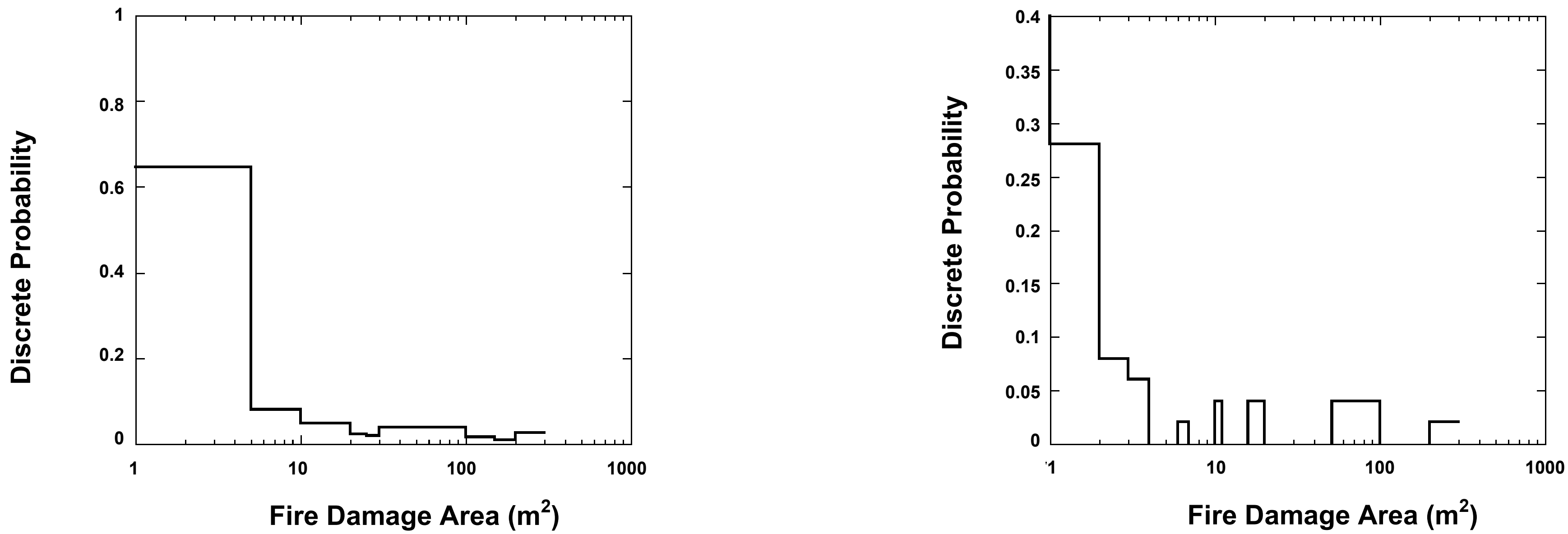


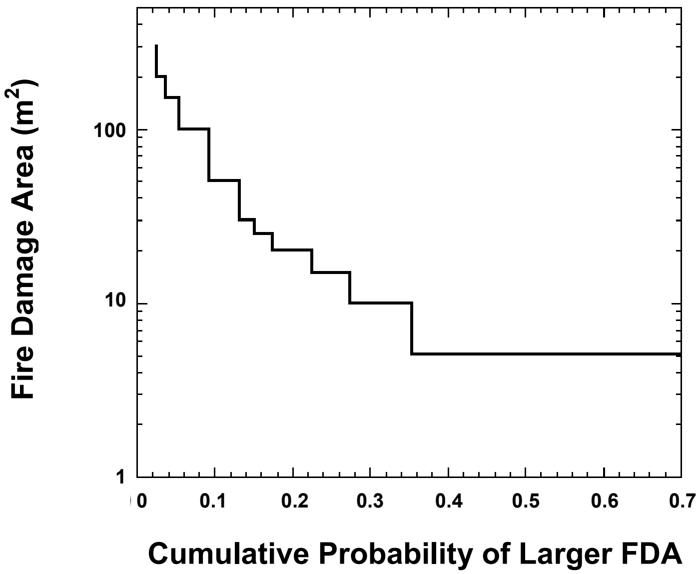
Figure 1: Number distribution of reported fire for office premises with and without sprinkler



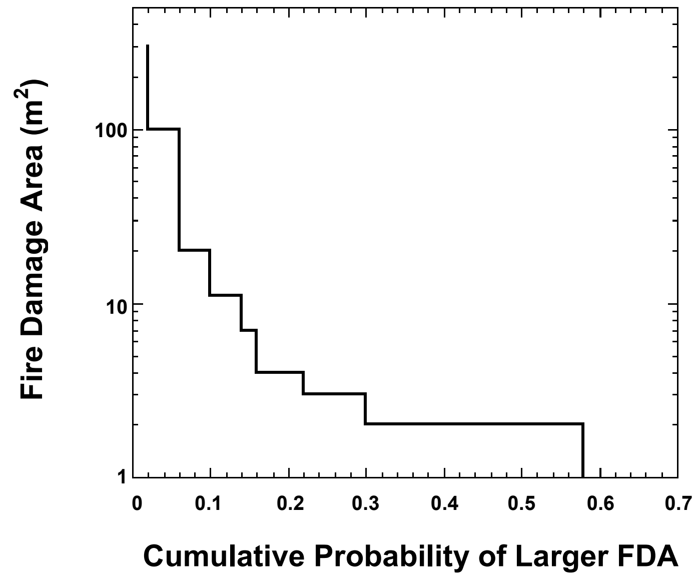
(a) No sprinkler

(b) With sprinkler

Figure 2: Discrete probability distribution of reported fire for office premises with and without sprinkler

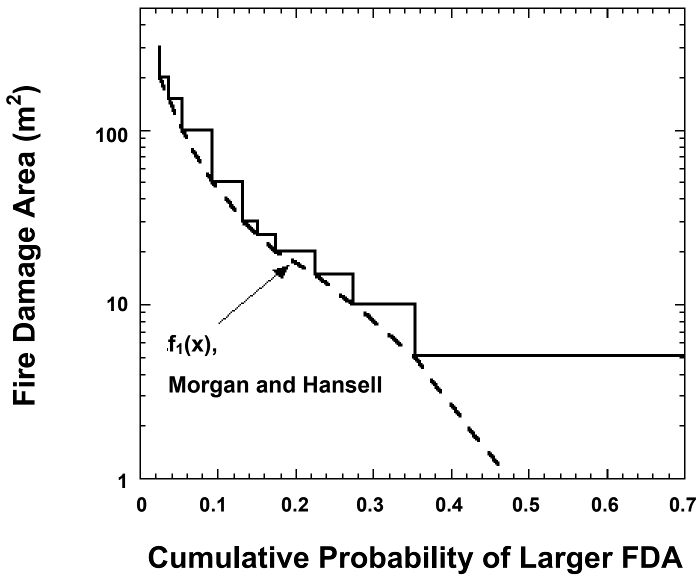


(a) No sprinkler

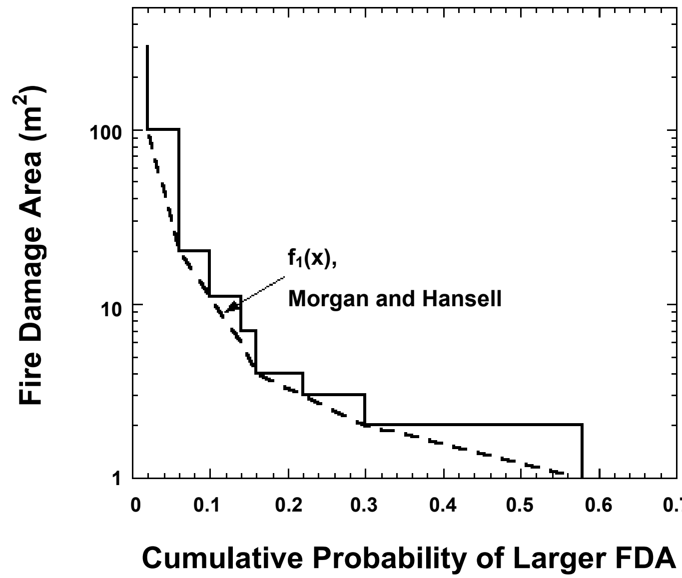


(b) With sprinkler

Figure 3: Cumulative probability distribution for reported fire for office premises with and without sprinkler



(a) No sprinkler



(b) With sprinkler

Figure 4: The cumulative probability function, $f_1(x)$, as utilized by Morgan and Hansell

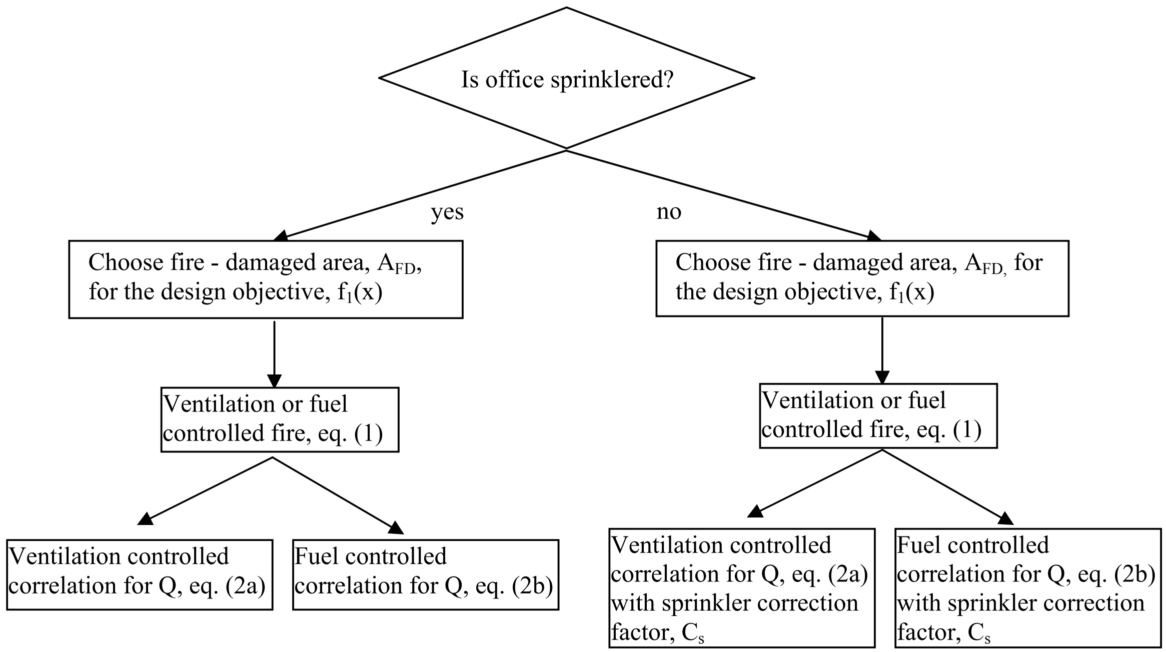


Figure 5: Sechmatics of the procedure used by Morgan and Hansell in the selection of the design fire

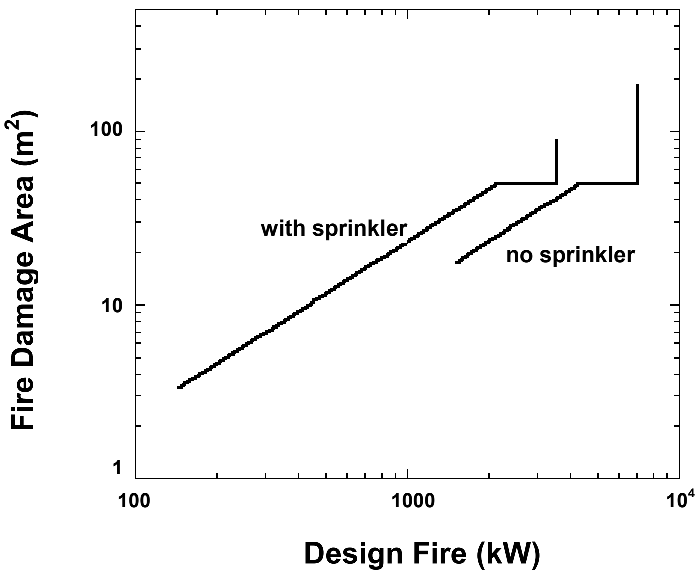
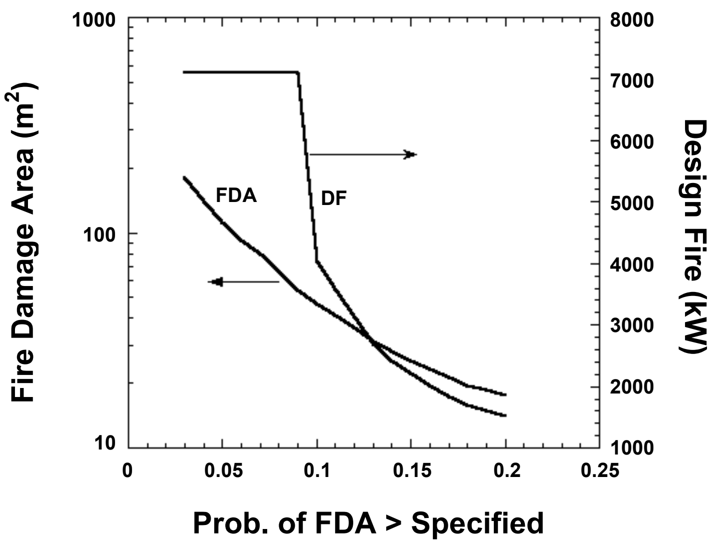
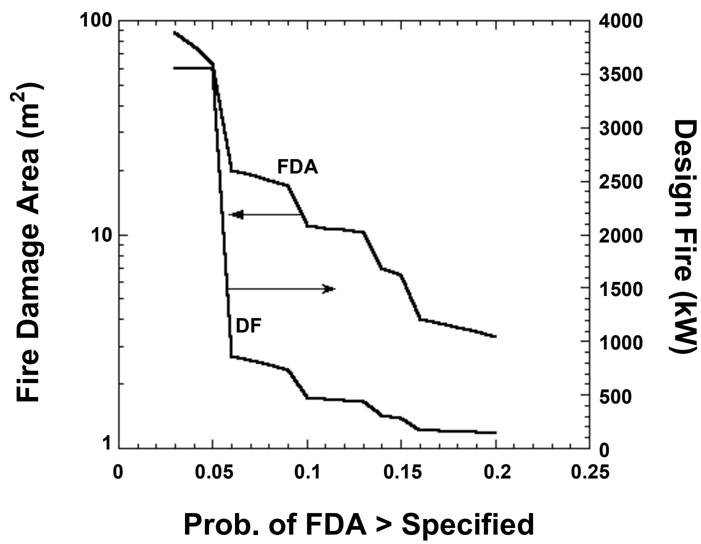


Figure 6: Relation between fire damage area and design fire according to equations (1), (2a) and (2b) with H = 3 m, A_w = 9 m^2

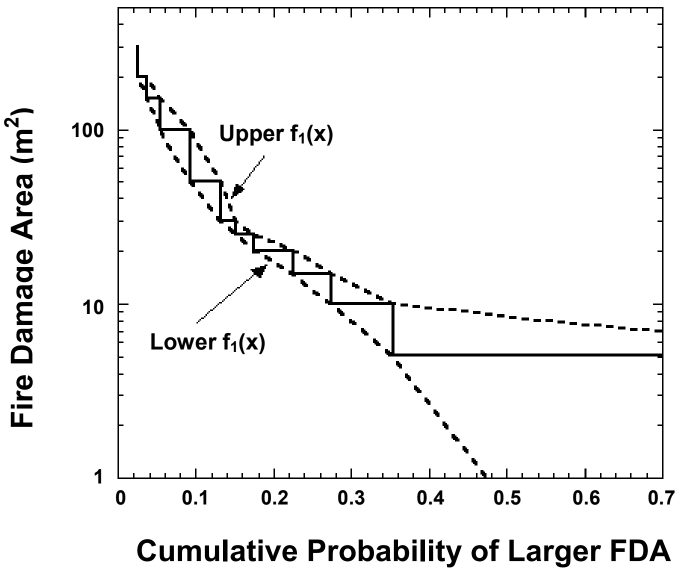


(a) No sprinkler

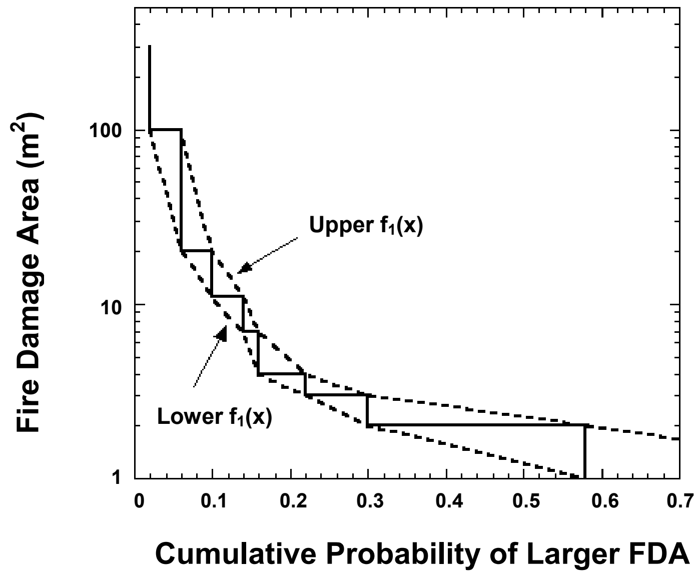


(b) With sprinkler

Figure 7: Fire damage area and design fire for an example ventilation setting (A_w = 9 m^2, H = 3 m) using the design approach of Figure 4

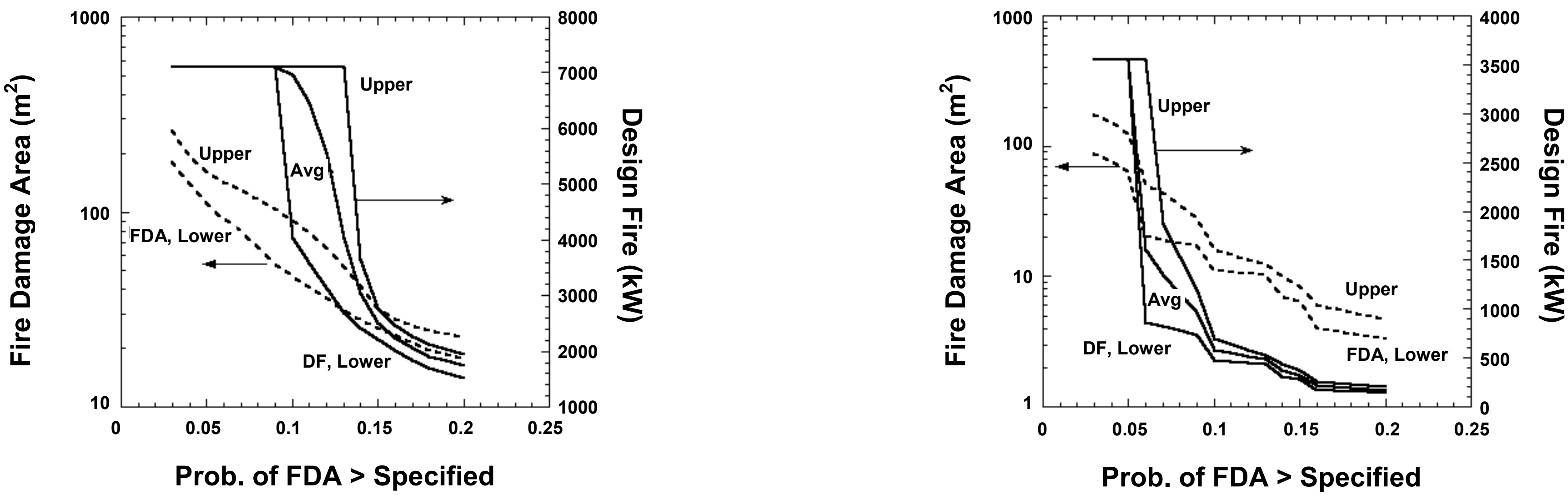


(a) No sprinkler



(b) With sprinkler

Figure 8: The upper bound and lower bound of the cumulative probability distribution, $f_1(x)$ for the sprinklered and unsprinklered case



(a) No sprinkler (b) With sprinkler

Figure 9: The upper bound, lower bound and average fire damage area and design fire for an example ventilation setting (A_w = 9 m^2, H = 3 m) using the design approach of Figure 4

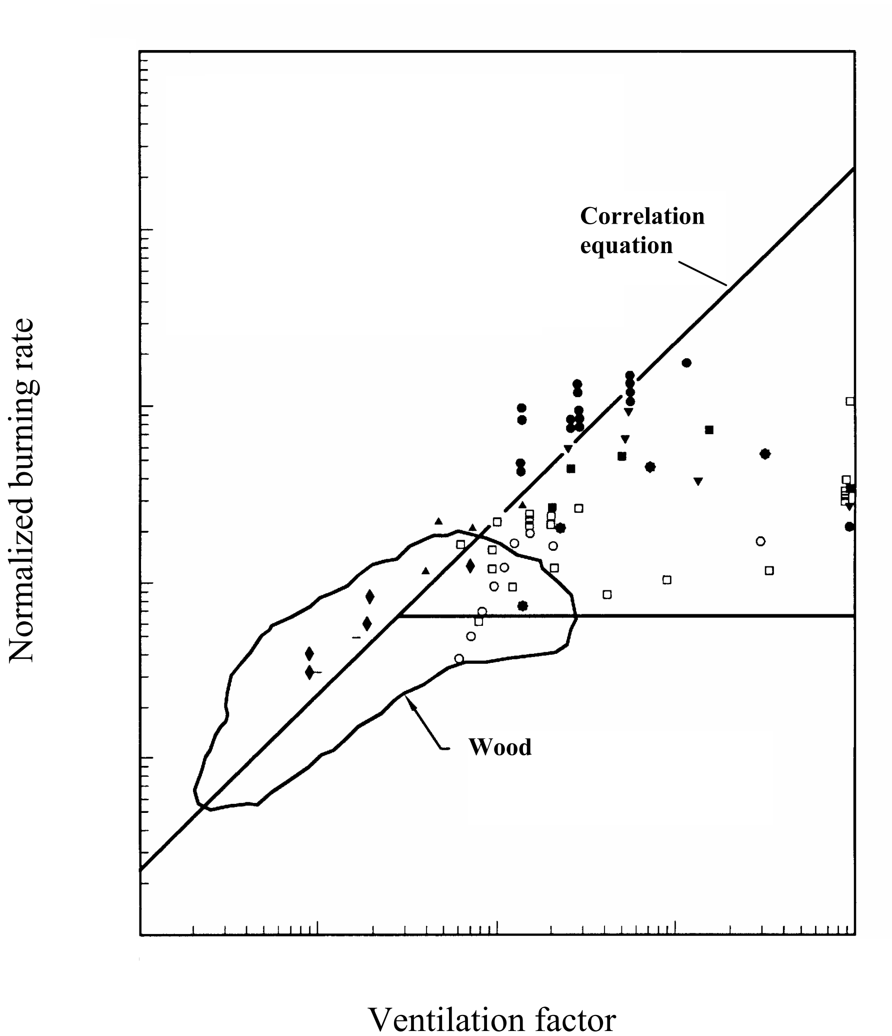


Figure 10: Data for transition from a ventilation-controlled fire to a fuel-bed controlled fire for various fuels [e.g. 17]

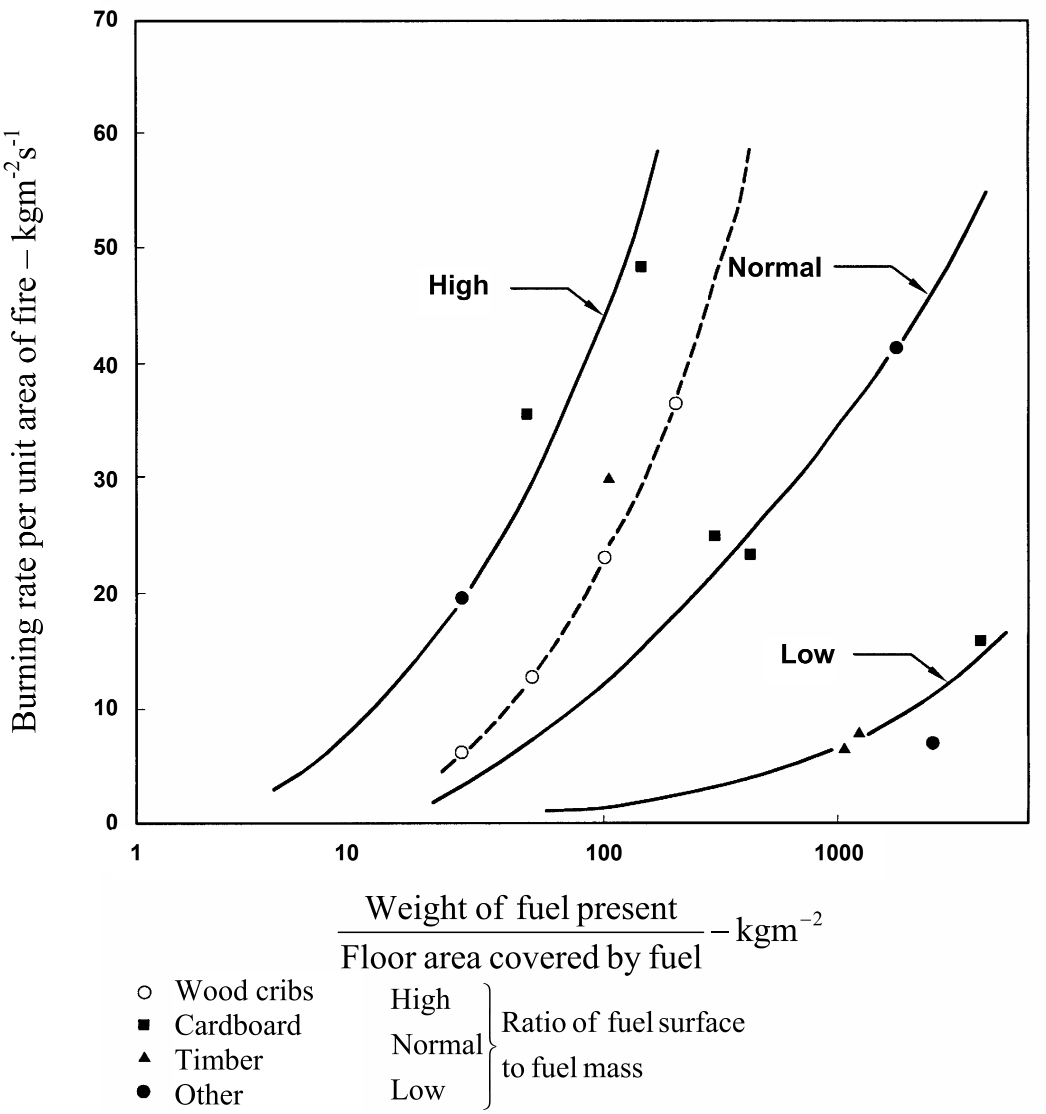
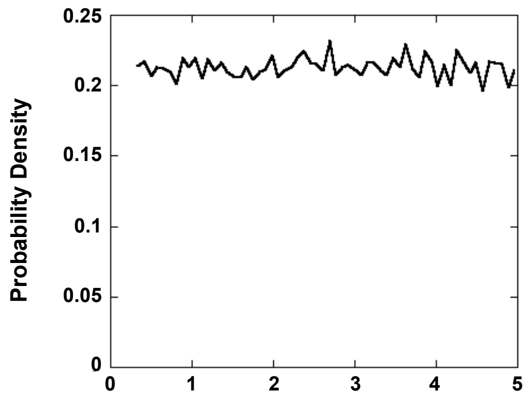
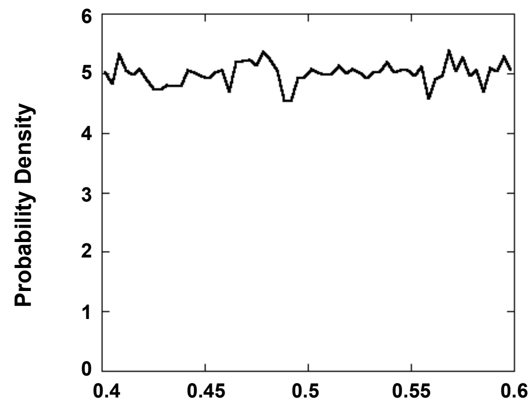


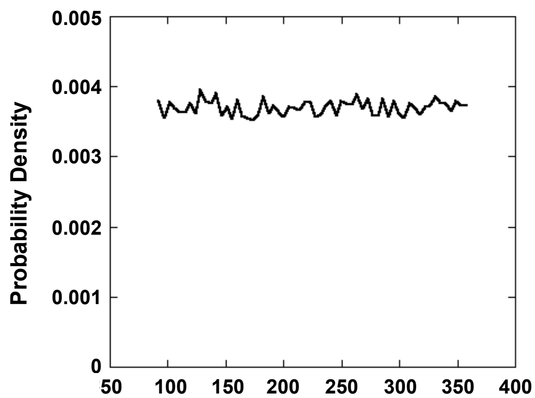
Figure 11: Rate of burning for fuels in various forms [12]



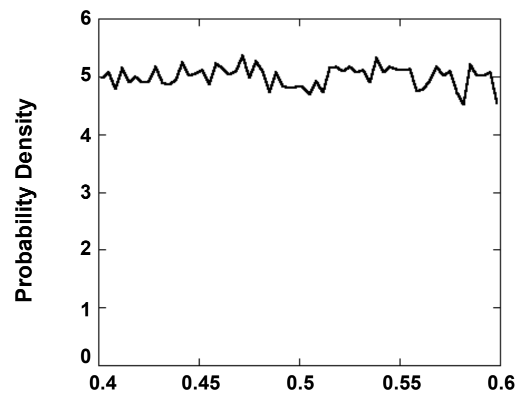
(a) C_t



(b) C_v



(c) C_{fb}



(d) C_s

Figure 12: Probability density distribution of the four parameters in the model after 50,000 samplings

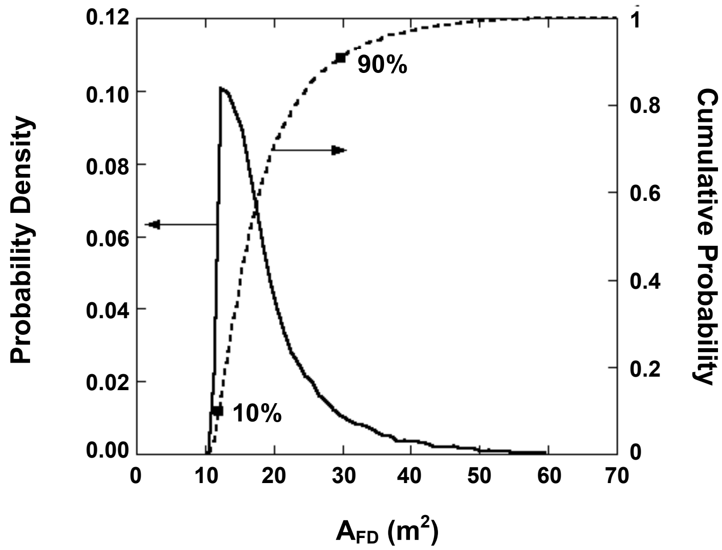
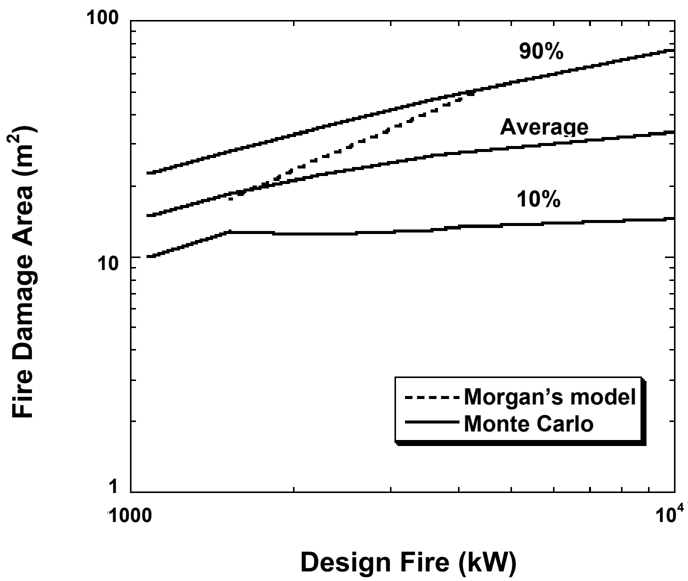
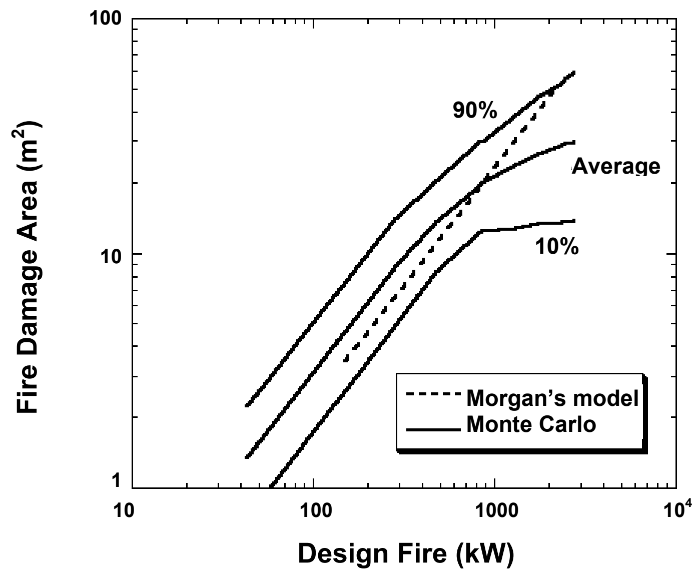


Figure 13: Probability density and cumulative probability distribution of the fire damage area for a case with sprinkler and Q_f = 800 kW

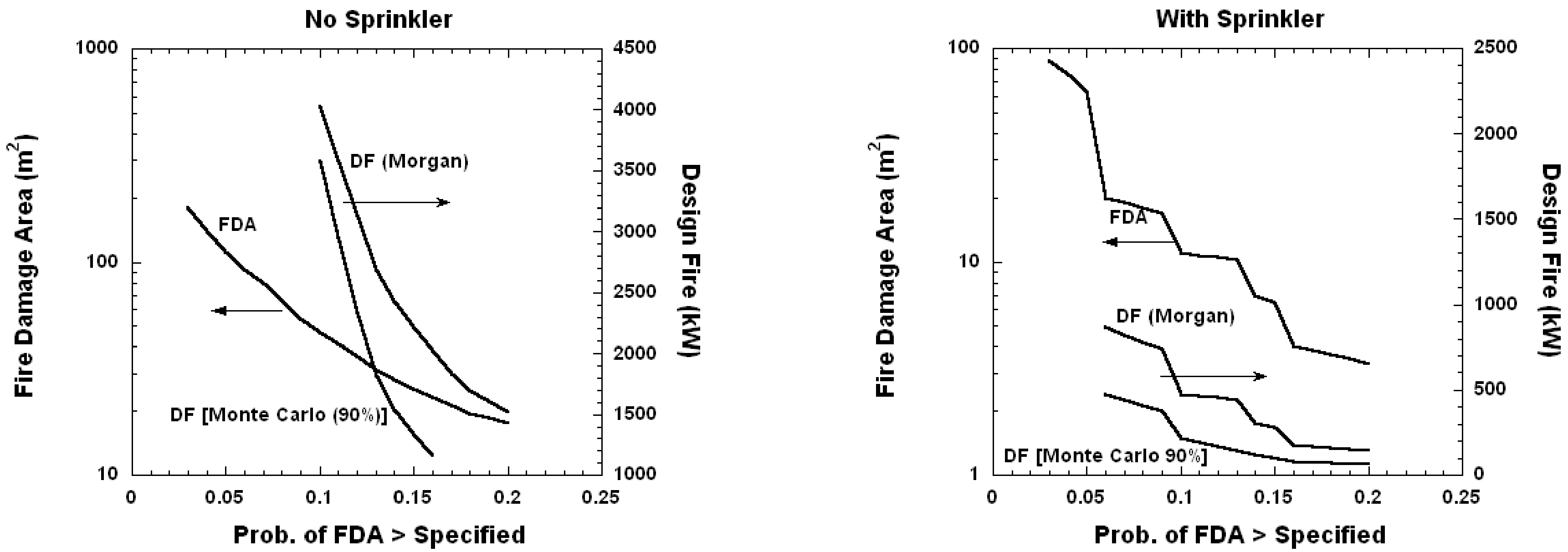


(a) No sprinkler



(b) With sprinkler

Figure 14: The variation of fire damage area with design fires accounting for the variation of parameters as represented by equations (4), (8), (10) and (11)



(a) No sprinkler

(b) With sprinkler

Figure 15: FDA and DF using the Morgan's approach and the Monte Carlo approach