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Report to FSH/14/-/2

DD9999, Task Group Activity: Commentary to a New Approach to Specifying Fire Resistance Periods

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1. BACKGROUND

The BSI committee FSH/14/-/2 is currently considering the comments that have been submitted in response to the Draft British Standard BS9999 which was issued for public consultation during 2002. As part of the consultation process, concerns were raised regarding the content of Section 7, which provided tables of fire resistance periods for different building occupancy groups which had been derived using a Time Equivalent fire engineering approach. Concerns were also raised regarding the recommended periods of fire resistance for buildings fitted with a automatic life safety sprinkler extinguishing systems.

While it was accepted that the use of the time equivalent method was a valid means of specifying fire resistance periods, the outputs and the methodology put forward in the standard, which involved non-qualified fire engineers to carry out there own calculations was considered to be unacceptable.

FSH/14/-/2 therefore formed a Task Group with the objectives to examine the use applicability of the Time Equivalent approach and to derive a new set of fire resistance periods whilst taking on board the comments made during the consultation process .

Dr Brian Kirby agreed to act as Convenor to the Task Group in which practising fire engineers with knowledge and experience in this particular field were invited to take a pro-active involvement. The active membership of the Task Group was made up of the following:

Dr Brian Kirby (convenor) - Corus Fire Engineering
Mr Gerald Newman - The Steel Construction Institute
Mr Neal Butterworh - Buro Happold (FEDRA)
Mr Jon Pagan - Warrington Fire Research Centre
Dr Craig English - WSP Fire Engineering
Dr Barbara Lane - Arup Fire
Dr Susan Lamont - Arup Fire
Mr Anthony Ferguson - Arup Fire
Mr Tom Lennon - Fire Research Station (BRE)
Mr Terry Day - Fire Research Station (BRE)

Between September 2002 and July 2003, the Task Group regularly met at intervals of 3 to 4 weeks to develop the analysis and achieve the objectives set by the BSI Committee. During this time, a range of fire engineering issues in relation to the task in hand, were discussed and resolved; this required a considerable amount of free time being devoted by individuals from the fire engineering community.

Figure 1 provides an overview of the analytical process and summarises the development of a robust engineering solution that the Task Group believe could be used to develop new fire resistance periods.

In the investigation, considerable time was spent in developing and validating software and conducting different forms of numerical analysis. This work was primarily undertaken by Corus Fire Engineering, The Steel Construction Institute, Buro Happold (FEDRA) and Warrington Fire Research Centre. An important part of this process was the comparison and interrogation of the analyses conducted by each organisation to ensure the outputs could be corroborated and provide a 'quality' check on the entire investigation.

2. TIME EQUIVALENT ANALYSIS

2.1 General

The ‘time equivalent’ technique is a method that is frequently used by engineers to determine what period of heating would be required in the standard fire test to provide the same maximum temperature in an element when heated by a natural or real fire. This technique has existed for a large number of years and various means of calculating the equivalent period of fire exposure have been developed. The most well known include;

Pettersson
Harmathy
Law
DIN 18230
CIB W14
Eurocode 1
A graphical analysis using heat transfer analysis and the parametric fire expression in Annexe A of Eurocode 1 was also developed.

The relationships described by Pettersson, Harmathy and Law were examined in detail and while it these are known to have been developed based upon experimental studies, they have been found to be limited either in their ease of use or scope of application.

Formulations described by DIN 18230, CIB W14 and Eurocode 1 are very similar in their approach with the main differences being in the treatment of the individual parameters.

The equation in Eurocode 1 was recently validated using experimental data as part of an ODPM PII project. This equation consists of ;

$$T_{e,d} = q_{f,d} \times k_b \times w_f \quad \text{(mins)}$$

Where;
$q_{f,d}$ = the design fire load (MJ/m^2)
k_b = an insulation factor for the compartment boundaries (min.m^2/MJ)
w_f = ventilation factor (dimensionless)

A correction factor, k_c, can also be applied which for the UK has been set equal to 1.0 for all construction materials.

Despite good correlation with experimental data the Eurocode equation does not lend itself to easy manipulation for a study of this type. In particular, factors for the insulation characteristics of the compartment boundaries change in broad steps rather than in gradual increments. It also does not consider the influence of fire growth rates which may be slow, medium of fast. The only way to incorporate these factors was to use a graphical method of analysis as a means of determining the equivalent period of fire exposure. This approach was therefore chosen for subsequent evaluation.

2.2 Graphical Analysis

2.2.1 Derivation of Te Using the Graphical Analysis

The graphical method is based upon correlating the maximum temperature attained by, for example, a protected steel member in a real fire, with an equivalent period of heating required to attain the same temperature in the Standard furnace. This is illustrated schematically in Figure 2 for a protected steel member and may be carried out using the following four steps;

Step 1

1. Derive a post flashover compartment fire using the parametric expression in Annexe A of Eurocode 1 using the following input parameters:

- Fire load density - data is presented in BS7974.
- The ventilation conditions - potential openings such as windows, doors etc.
- The compartment geometry - the height of the compartment will significantly influence the average temperature with tall compartments generally being less onerous.
- Fire growth rate - occupancy dependent.
- Thermal properties of the compartment/enclosure - walls, floor, ceiling (multi-layered wall constructions can also be considered).

Step 2

Using heat transfer analysis, establish the thermal cycle of the structural element using the following data:

- Size of member - for steel, Hp/A.
- Thermal properties of the member - specific heat, thermal conductivity, density.
- Thermal properties of any protection - specific heat, thermal conductivity, density.
- Heat transfer coefficients for radiation and convection.
- Surface emissivity of the member.

Step 3

Using the same, thermal and physical input data for the structural member as described in Step 2, calculate the heating curve of the member under Standard furnace heating conditions, BS EN1363.

Step 4

The value of time equivalent can then be derived by correlating the maximum temperature attained by the structural member in the parametric fire with the time it takes to attain the same temperature under Standard furnace heating conditions.

Depending upon the severity of the real fire, the value of Te may be achieved either in a shorter or longer period than the duration taken to achieve the maximum temperature in the parametric analysis, i.e. a short duration fire may achieve a maximum steel temperature in a time that is less than the time taken to achieve the same temperature in the standard furnace fire. Conversely, a long low temperature fire will achieve a maximum steel temperature in a period exceeding the time it takes to achieve the same temperature in the standard furnace fire.

This procedure is independent of the type of structural material (protected steel, concrete, timber etc), the failure temperature / maximum temperature, or the type and thickness of any fire protection material. It also only applies to post flashover fires. However, it does depend upon an accurate representation of a real fire during the post – flashover stage.

2.2.2 Parametric Expressions

The parametric relationships now described in EC1-1-2 were originally based upon research carried out by Pettersson in the 1970's. This work involved developing a heat balance approach for predicting the thermal cycles of post flashover fires taking into account the fire load density, ventilation conditions, compartment geometry and the type of materials used in the construction of the compartment/enclosure. Pettersson's analysis is not easy to compute and the methodology for adjusting the severity of the fire to reflect changes in the thermal properties of the construction materials used in the compartment boundaries, are difficult to apply and limited in their application.

In the preparation of ENV 1991-2-2, a modified form of Pettersson's analysis was adopted that enabled the temperature time response of a natural fire to be modelled in the form of a set of parametric relationships. During the conversion of the ENV into a full EN (EC1-1-2), the relationships were further modified to take account of more recent full-scale fire test data. The parametric expressions now consider the fire growth rate and the treatment for quantifying the influence of the thermal properties of the compartment boundaries on the total fire behaviour.

As part of an ODPM PII project, the parametric expressions have recently been validated against a large body of fire data from tests conducted in the UK by Corus Fire Engineering [this missed this bit out Brian] and FRS (BRE). In the majority of cases, an excellent correlation was achieved between the test data and the analytical calculations. In instances where the correlation was not so good, predictions of the fire conditions were more onerous and thus the results where conservative.

2.3 Correlation Between the Graphical Method and EC1-1-2 (Equation)

In order to give confidence in the graphical analytical method, the results of the outputs were compared to those derived using the direct equivalent fire resistance calculation given in EC1-1-2.

Whilst individual cases could be identified in which there was a difference in the predicted fire severities using the two methods, when averaged out over a large number of analyses, the results were very similar. This factor is illustrated in Figure 3, which shows a direct comparison between the outputs from the graphical approach compared with the analyses using the EC1-1-2 equation.

The two methods were also compared in terms of the outputs resulting from a Monte Carlo statistical analysis in which a very large number of fire scenarios (up to 10,000 randomly generated fire simulations) were analysed to determine a cumulative plot of Time Equivalent fire resistance periods. This analytical technique is discussed in detail in the later sections of this report. Insofar as this comparison is concerned, good correlation was achieved between the graphical method and EC1-1-2 as illustrated in Figure 4.

2.4 Issues

In applying any Time Equivalent analysis, key decisions are required with respect the values that should be used for each design parameter. The sensitivity of the results varies considerably with the values chosen for each variable. This aspect is considred in the following sections:

2.4.1 Fire Load

It is normal practice in developing a fire safety engineering solution to refer to a design fire load density appropriate to the occupancy type. In the UK, it is customary to either carry out a job specific fire load survey or to refer to statistical survey data that is reported in published documents such as BS7974. These values are represented in cumulative form. In theory the higher the chosen fractile value the less likely it is that the actual value in practice will exceed this and thus the design safety margin will increase because the uncertainty attached to the value has been reduced. However, using these values poses a significant problem in that it is uneconomical to prepare engineering calculations use a absolute worst case set of values for all design variables but if the worst case value is not chosen then the design may be unsafe. Structural fire engineering design guidance documents recommend that ‘deemed credible worst case values are used for design variable such as fire load. Generally an 80% fractile is recommended. However for very tall buildings designing for it may be appropriate to further eliminate the likelihood that this fractile values will be exceeded in practice. For example, maybe a 90% or 95% fractile should be adopted for tall buildings in recognition of the increased consequences of failure. Its difficult to link the recommended fire load fractile value with risk of structural failure for Regulatory purposes.

2.4.2 Ventilation Conditions

The maximum ventilation condition can usually be established based upon the architectural design. However, this would assume knowledge of the fit out where compartments may be separated into enclosures, and which can alter in the lifetime of the structure. The proportion of windows that may fail during the fire process and other factors such as whether doors to rooms are open or closed at the time fire start is another factor of uncertainty. Some engineers would adopt a ventilation condition that gives rise to the most onerous fire condition although it is important to realise that the maximum ventilation may not be the most onerous fire condition. This is particularly so for protected steel members.

After the fire load, specifying the ventilation conditions is the next most important parameter to be established since this controls the rate of fire development, the temperatures attained during the fire and the duration of the cooling phase. It is not possible to specify a single 'catch all' ventilation condition for all buildings types within a single occupancy to determine the most onerous condition, particularly when the parameter can be influenced by other factors.

2.4.3 Compartment Thermal Properties

Heat generated during a fire is lost through the walls, floor and ceiling and therefore the thermal properties of the materials used in the construction of the building / compartment influence the severity of the heating conditions. Where the thermal properties can be defined for a building or compartment, these may be used in the calculations. However, to simplify the calculations and for the general case, a single value can be adopted which will generally give rise to the more onerous fire condition.

It was recognised that with changes in Regulations reflecting environmental concerns on the thermal performance of new buildings (Building Regulations Part L), a single low value for the thermal diffusivity of the compartment construction should be chosen for all calculations. This was regarded as representative of the materials used in a reasonably well-insulated structure and would be typical of a modern dwelling or an office building.

2.4.4 Compartment Geometry

The geometry of the compartment influences the temperatures attained during the fire. Since some heat is lost to the surrounding surfaces, a tall compartment will usually result in lower atmosphere temperatures than one will find in low compartments. A reasonable upper limit to the compartment height can be applied that is typical for the particular occupancy in the knowledge that, if the height is increased further, the temperatures attained should not increase.

With regards to the floor area, once this reaches a particular size, any further increase in plan will have little effect on the overall temperatures attained, see Figure 4. However, for small compartments e.g. a dwelling, the choice of compartment size is significant.

2.5 Solutions

It is clear from the discussion in section 2.4 that, to provide a set of fire conditions as a 'catch-all' for each occupancy and use these to determine the Time Equivalent as a basis for providing prescriptive solutions is difficult. A statistical technique was therefore required that would allow a very large number of permutations of fire load density, ventilation conditions, compartment geometries to be analysed for subsequent evaluation based upon a risk / consequence form of analysis.

A Monte Carlo method of analysis was therefore developed to enable many thousands of potential fire scenarios to be evaluated for each occupancy type.

3 MONTE CARLO ANALYSIS

3.1 General Discussion on Technique

The Monte Carlo technique is applicable to problems of a stochastic or probabilistic nature. It involves the simulation of a large sample of typical fire scenarios during which values for each design variable are chosen at random for input into engineering calculations. This makes up the probabilistic element of the methodology.

Probability distributions are required for each part of the model system. These can be derived from expert judgement, statistical data or real life observations and confidence in the results may be enhanced if the relationships built into the model are based upon accepted scientific theory supported by experimental data. Such simulation-based approaches are advantageous as they are based upon physical theory and experimental measurement and this can be used to compensate for a lack of information about real fires in a manner that other methods for calculating risk cannot. Furthermore, the assumptions made in these simulation models are explicit and a measure can be made of the sensitivity of these assumptions on the calculated risks by changing the values for each variable, recalculating the risk and comparing this new risk measure with that originally calculated. The sensitivity analysis can then be used to determine which variables have the greatest influence on the calculated risks and which variables are relatively unimportant.

The Monte Carlo method of analysis is ideally suited to practical applications since there is the opportunity to include a high level of detail and any shaped distribution can be used from which values can be chosen at random for use in engineering calculations(2). However, the values must be compatible with the known statistical distributions.

For example, in the UK Fire Safety Engineering Code, BS7974, data is provided in PD1(3) on the fire load densities for several occupancies at the 80%, 90%, 95% fractile levels. Average values are also given. Therefore, if 10,000 values of fire load are selected they must conform to a statistical distribution fixed around the known datum points. In this particular example, a methodology was developed that enabled the full distribution of fire load densities to be described.

Other variables such as room size, minimum and maximum window opening areas and room heights where inputted into the model based upon engineering judgement. 10,000 fire simulations where then run to provide a random plot of fire resistance periods.

The Monte Carlo methodology for deriving measures of equivalent periods of fire exposure is illustrated in Figure 6 and is described using the following psuedo computer code.

```
Number of trials = 10000

For I = 1 to Number of trials
     Select fire load
     Select compartment size
     Select ventilation
     Select compartment insulation properties
     Select section size
     Select fire protection thickness
     Compute and store time equivalent
Next I
```

At the end of the process, 10,000 values of time equivalent are stored. It is convenient to plot these as percentage fractiles. For example, the 80% fractile is the value of time equivalent which is only exceeded in 2,000 of the 10,000 cases and the 90% fractile is corresponds to the value that is only exceeded in 1,000 of the 10,000 cases. A typical plot of % fractile values vs time equivalent periods is shown in Figure 7.

The shape of the curve in Figure 7 depends on the statistical data and the engineering model used. In this example, the initial sharp rise in the curve is a function of one of the coefficients used in the parametric fire curve specified in EC1-1-2.

3.2 Input Parameters - Fire Analysis

3.2.1 Fire Load Distribution, BS 7974

In BS7974 fire load densities are provided for a range of occupancies. These are given for each of the following fractiles; 80%, 90% and 95%. Average values are also provided.

To carry out a Monte Carlo analysis a complete frequency distribution diagram is required that include points which fall between 0 and 80%. The upper end fractile values where constructed using the data provided in BS7974 as follows:

1. Chose a high value that represents the 100% fractile.
   This is set based on expert judgement

2. Chose a value for the minimum fire load.
   This is set based on expert judgement, typically 10% of the 80% fractile value. This is also supported by statistical information given in European studies and have been reported by Pettersson [ref]

3 Chose two values of fractiles between zero and 80%, typically 30% and 50%.

4. Construct the relative frequency diagram using integration.

Knowing, that the total area under the curve is 100%, the relative frequencies for all fractiles and the average fire load can be calculated (Figure 8). Depending upon the values chosen for the fractiles between zero and 80%, the negative or improbable values for some frequencies may be found. For example, the frequency for a fractile less than 80% is unlikely to be less than the 80% value. Simple rules were therefore developed to ensure that the distribution of fire load densities calculated did not result in any fractile value being obtained that was less than the corresponding datum value given in BS7974.

In selecting the fire load densities corresponding to the 100% fractile, the values chosen were substantially above the design values often used for that particular occupancy. For example, for offices the 80%, 90% and 95% fractiles correspond to 570, 670 and 760 MJ/m^2 respectively, with the result that the value selected for the 100% fractile = 1200MJ/m^2.

In order to determine the fire load frequency distribution that provided the best fit to existing published data, it was generally found that the fire load density corresponding to the 0% fractile was well above zero. For example, in offices, the fire load density corresponding to the 0% fractile was 57MJ/m^2. In the subsequent Monte Carlo analysis, this had the effect of making the output of cumulative distribution more onerous at the lower values than if the 0% fractile was deliberately fixed at zero fire load density. The adoption of fire load densities above zero at the 0% fractile can also be supported by studies conducted in Europe.

The fire load densities adopted for each of the occupancy groups are given in Tables 1a and 1b.

3.2.2 Sprinklers:

As part of the analyses, the influence of automatic extinguishing systems on Time Equivalent were considered and a separate set of Monte Carlo analyses was carried out for each occupancy in which the fire load density was factored by 0.61 to reflect the reduction in fire severity. This value was derived in the course of a major research programme carried out in Europe under the heading 'Natural Fire Safety Concept'. The work involved a detailed study on the risk factors (including reliability) associated with automatic extinguishing systems used in buildings. The value of 0.61 was the highest of the factors put forward, which is now recommended in Eurocode 1-1-2 and has been proposed for adoption by the UK in its National Annexe ?.

3.2.3 Ventilation

The ventilation conditions chosen for the compartment are based upon an assessment of the openings that may be incorporated in each specific type of occupancy. These are described as follows:

i. Range of ventilation areas expressed as a percentage of the floor area.

ii. Range of ventilation heights expressed as a proportion of the compartment height. (It is recognised that in some buildings glazing may occupy almost the full floor to ceiling height).

The benefits of a Monte Carlo analysis become clear in overcoming the dilemma of prescribing a specific ventilation opening factor to derive the parametric fire. The ventilation parameter can vary considerably in the design and layout of buildings and will usually change significantly during the fire process itself. Therefore, by analysing a large number of permutations such as 10,000, a wide range of fire scenarios can be considered.

Without any other published data being available on the relative proportions of ventilation area and height with respect to floor area and floor-to-floor height, in the Monte Carlo analysis the selection of the input values into the calculation process were set as a square distribution between the stated limits. These are presented in Tables 2a and 2b.

3.2.4 Geometry

Expert judgment was used to estimate compartment sizes. Generally figure considered to be realistic for a particular occupancy in terms of the minimum and maximum floor area and compartment height was used. While upper limits are placed on the compartment height, increasing this dimension beyond the values considered gives rise to a less onerous fire condition. A minimum compartment height was also chosen based upon an acceptable lower limit for a habitable room.

With regards to the floor area, the parametric outputs are not strongly dependent on this parameter and it is found that once a floor exceeds a certain size, increasing its dimensions has no significant effect on the results (see Figure 4). Residential buildings and hotel rooms are an exception where it is customary to design small compartments.

Without any other published data on the relative distribution of floor areas and compartment heights, in the Monte Carlo analysis, a square distribution was therefore adopted between the limits of the parameters set for each occupancy. These are given in Tables 3a and 3b. In some occupancies a single value has been set to the floor area and/or the compartment height.

3.2.5 Compartment Insulation Properties

In the analysis a conservative approach was taken in which the compartment or building is assumed to be reasonably well insulated. A value for the thermal diffusivity of $\sqrt{\rho\varsigma\lambda}$ = 720J/$m^2s^{1/2}$K was therefore adopted.

3.2.6 Fire Growth Rate

For each occupancy type, the fire growth rate adopted in the parametric analysis aligned with the recommendations given in both BS7974 and EC1-1-2 was used.

3.3 Input Parameters - Heat Transfer Analysis

Heat transfer calculations were carried out using the relationships provided in Eurocodes 1 and 3 for both the real fire and Standard furnace heating conditions. These have been previously validated against UK test data as part of the calibration process being conducted for all the Eurocodes

In the Monte Carlo analysis the section factor (Hp/A) for the steel member was chosen between the limits 70 to 220 m^{-1} with a triangular distribution set between the extremes to reflect the distribution of member sizes found in buildings.

A single type of fire protection material was used throughout the studies and the physical and thermal properties were those of spray vermiculite cement with the following characteristics:

⑧ = 550kg/m^3
⑩ = 1200 J/Kg^0K
② = 0.2W/m^0K

The thickness of the fire protection was randomly selected in the calculation process. The maximum steel temperature was then calculated and the corresponding time equivalent period calculated

3.4 Sensitivity Checks

In the analysis, a continuous process of checks on sensitivity of the input parameters with respect to the outputs was undertaken.

For consistency it was found that up to, 10,000 cases were required in the Monte Carlo analysis to ensure a sufficient population was selected at the extremities of the cumulative fractile distributions. The relationship between the number of simulations and the accuracy of the shape of the cumulative distributions follows a relationship more commonly know as ‘the diminishing law of returns. Four hundred fire simulations is known to provide an accuracy level of +/- 5% on the mean value. This accuracy level can be calculated by dividing unity by the square root of the number of simulations. Ten thousand simulations increase the accuracy to + / - 1%.

The influence of floor area and whether the lower fractile values of fire load density are taken through zero have already been discussed.

The sensitivity of the outputs with respect to the thermal diffusivity of the compartment construction materials on the fire process was evaluated. In the analysis, a single value of 720 $J/m^2s^{1/2}K$ was considered representative of a reasonable level of insulation for an occupied building. Figure 9 shows the influence of varying the thermal diffusivity on the cumulative fractile outputs for Time equivalent in which 1080 $J/m^2s^{1/2}K$ is typical of a blockwork/concrete construction and 360 $J/m^2s^{1/2}K$ represents a highly insulated compartment. The greatest influence of this parameter occurs at the lower and less important fire resistance periods, and at higher values of Te, the value 720 $J/m^2s^{1/2}K$ adopted in the analysis represents a realistic and conservative approach.

3.5 Outputs

Each occupancy type was analysed as described in the preceding sections for both sprinklered and non-sprinklered buildings. The results are presented in Figures 10 to 19 in the form of cumulative Fractile % distributions vs Time Equivalent.

In essence, Figures 10 to 19 represent the Engineering outputs from the work and form the basis of subsequent risk and consequence analysis.

4. ANALYSIS OF THE OUTPUTS

Having established the Cumulative Distribution Curves using a Monte Carlo analysis, a methodology was required for determining appropriate fire resistance periods. Traditionally, fire resistance periods are specified according to the building purpose group and height. The purpose group influences the fire severity and the evacuation characteristics (familiarity and alertness), and the building height influences fire fighting and the consequences of failure. It was agreed that the concept of varying the fire resistance according to purpose group and height is valid but that a more transparent and scientific method was required.

The cumulative distribution curves account for the fire severity in engineering terms, but they do not account for the evacuation characteristics, fire fighting, or the consequences of failure. Therefore, the proposed solution was to;

1. Define appropriate height categories that reflect fire fighting requirements.
2. Use a risk-based methodology to account for the consequences of failure.
3. Adjust the fire resistance periods to account for the evacuation characteristics.

4.1 Building Height Categories Limits

Using the height of a building as a means of classifying fire resistance is limited in that there is a step change in the recommended period of fire resistance at each interval that does not necessarily correlate to a step change in risk. For example, a building that is 18.1m high has virtually the same risk as a building 17.9m high although this height corresponds to the reach of a fire fighting ladder. However, the alternative would be to introduce a significantly increased complication to the process and therefore a simple route to designating height bands was chosen.

The height bands currently given in Approved Document B are:
 a) Less than 5m
 b) Between 5m and 18m
 c) Between 18m and 30m
 d) Over 30m.

The original historical justification for some of these heights are understood to be based on criteria such as for example; the height of fire brigade ladders. These are possibly now out of date since the equipment used by the various fire brigades for gaining access to buildings has changed over the years. They also vary throughout the country and between different authorities. However, it was considered that there was no particular need to change these criteria particularly as they have been proposed in BS9999.

The task group considered that two new height criteria should be introduced:
 a) 11m height
 b) 60m height

4.1.1 New 11m Height Criteria

The 5m height limitation currently prescribed in the AD-B generally corresponds to differentiating between single and two storey buildings. The next step change in fire resistance occurs at 18m and this was considered excessive. Therefore, by introducing an 11m category enables buildings that are 2 or 3 storeys in height to be differentiated from buildings that have typically 4 to 6 storeys. A height limitation of 11m is also referenced in the AD-B when considering escape from small single stair buildings.

4.1.2 New 60m height criteria

Since there is currently no change in the recommendations for buildings 31m high compared to those that may be as high as 200m high, a new 60m height criteria was introduced. In practice, very tall buildings tend to be 'landmark' structures and these would generally be designed with fire consultants included on the project teams. Therefore, the level of fire safety would likely be specified by a fire engineering analysis rather than application of a prescriptive tabular approach such as BS9999. However, it was considered sensible to segregate the recommendations for very tall buildings.

The 60m height limitation was based upon the level at which wet rising mains are typically required (rather than dry mains). It also corresponds to the reach of modern inner city high-reach appliances and therefore the step change at this point was considered a reasonable reflection of a change in fire fighting devices/procedures.

4.1.3 Summary of Recommended Height Criteria

The recommended height criteria as presented below were therefore adopted for further analysis of risk and consequence.

Building height	**Generic description**
Less than 5m	Single storey buildings
Between 5m and 11m	Typically 2 to 3 storeys
Between 11m and 18m	Typically 3 to 5 storeys
Between 18m and 30m	Typically 5 to 6 storeys
Between 30m and 60m	Reasonably tall buildings
Over 60m	Exceptionally tall buildings

Note: In accordance with the AD-B the number of storeys would depend on the floor-to-floor height.

For basement storeys, the height limitations given in Approved Document B were considered reasonable and there was therefore no justification for change.

4.2 Risk Concept and Method

The concept of risk is neither new nor unfamiliar to the fire industry. In fact, existing methods for specifying fire resistance are already loosely based on the concept of risk.

Risk can be expressed as a function of frequency, probability and consequence as below:

Risk = frequency x probability x consequence

Frequency:
The frequency is a measure of the number of fires that are likely to occur in a particular building in a given period and is a function of many factors such as the purpose group, type and quantity of combustible materials, ignition sources etc.

One of the main influences on the frequency of fires is the size of the building. To reflect this accurately it should be a function of the floor area and number of storeys but for simplicity, it can be related to the building height. This is not unreasonable since it is post-flashover fires that are of interest and flashover is unlikely in large open floor plates. Therefore, height has been adopted as the basis of setting acceptable criteria.

Probability:
The probability of failure is directly related to the cumulative distribution curves that resulted from the Monte Carlo analyses. Therefore:

$$\text{Probability} = 1 - \text{Fractile} / 100$$

Consequence:
The consequence due to fire is the damage that would occur if the time-equivalent period were exceeded. This is significantly influenced by the element that fails and how it fails, but for the purposes of the calculations, absolute failure of the whole structure has generally been assumed. This typically means that more than one column fails. Therefore:

$$\text{Consequence} \propto \text{height}$$

4.2.1 Basis of acceptable criteria

In any risk-based method, it is necessary to define the acceptable risk. Ideally, this is expressed quantitatively in absolute terms but it is difficult to assign definitive values for the acceptable risk. The acceptable risk will also change with perceived consequence. For example, society is less comfortable with multiple deaths than many single deaths.

For the purposes of specifying fire resistance, the primary objective is to ensure that the relative risks are similar. Therefore, for simplicity it is acceptable to assume that that the acceptable risk is constant and to assess the relative risk of different purpose groups and heights. Using the equations above, a height of 18m and the 80% fractile value from the cumulative distribution curves the acceptance criterion for the relative risks can be calculated as follows:

$$\text{Risk} = \text{frequency x probability x consequence}$$

$$\text{Risk} \propto \text{height x } (1 - \text{fractile} / 100) \text{ x height}$$

$$\text{Risk} \propto (1 - \text{fractile} / 100) \text{ x } h^2$$

$$\text{Risk} \propto (1 - 80 / 100) \text{ x } 18^2$$

$\underline{\text{Risk} \propto 64.8}$

The use of 18m and the 80% fractile are justifiable on the basis that the 80% value is usually adopted as the "safe" value for fire safety design and fire fighters are normally required to enter a building for search and rescue.

Having established an acceptance criterion for the relative risk based on a building height of 18m, it is then possible to determine the fractiles that produce the same risk for other building heights. These are presented in Table 4, which lists the appropriate fractile for each height group as well as a consequence rating.

4.3 Evacuation characteristics

The fractiles proposed in Table 4 are acceptable for buildings with similar evacuation characteristics but it is considered that the fire resistance period should also reflect differences in evacuation characteristics. There are three primary issues regarding the evacuation characteristics;

- familiarity of the occupants,
- alertness of the occupants (awake or asleep)
- the period of evacuation (phased or simultaneous).

The familiarity of the occupants affects the evacuation period but only slightly and usually only in the first few minutes of the fire duration. Therefore, the familiarity of the occupants should not affect the fire resistance period. It is also considered that phased evacuation should not increase the fire resistance period. This is because phased evacuation is precluded from certain buildings, necessitates compartment floors and an automatic fire warning system all of which are considered to compensate for any additional risk. Furthermore, phased evacuation is only economical at a height of approximately over 30m (it is at this height where phased evacuation produces narrower stair widths than simultaneous evacuation).

Conversely, it is considered that buildings containing a sleeping risk should have a higher fire resistance period than similar buildings with no sleeping risk. This recognises that a sleeping occupant may not be aware of a fire and therefore an additional factor of safety is required. To ensure these risks are reflected in the specification of the fire resistance, a factor of safety is introduced by increasing the consequence rating by one category. It is also considered that a further factor of safety is required in buildings in which evacuation could not be completed or relied upon e.g. medical care. Under these circumstances, the consequence rating should be increased by a factor of 2.

The proposed adjustments by risk are given in Table 7.

An example of this type of adjustment can be illustrated by referring to Tables 4 and 7:

A residential building between 11m and 18m high has a consequence rating of 4 (3 plus 1). Therefore, to determine the fire resistance period for this risk, reference is made to the 92.8% fractile on the cumulative time equivalent output for residential (dwelling) buildings. In this particular case for a non-sprinklered building, a fire resistance of 102 minutes is required as indicated in Table 8.

5. RESULTS AND RECOMMENDATIONS

Fire resistance periods were determined using the cumulative distribution curves derived for each purpose group for both non-sprinklered and sprinklered buildings. These are presented in Tables 5 and 6 respectively and have been based upon the consequence ratings and fractiles as presented in Table 4. At the very low values the outputs are influenced by the analytical procedure and for this reason either less than '15' or '30' minutes is stated. All other values are quoted to the nearest minute.

The adjustment values contained within Table 7 were then used to generate the fire resistance periods for each purpose group with respect to building height (see Tables 8 and 10).

Finally, Tables 9 and 11 provide fire resistance periods for each purpose group with respect to height once they have been rounded, generally upwards to the nearest 15-minute interval - the exception being when the fire resistance exceeds a category by only 1 or 2 minutes.

5.1 Justification of Footnotes to Tables

Tables 9 and 11 contain footnotes that recommend revised fire resistance periods for certain situations. These are discussed below.

15 minute fire resistance period:

A fire resistance period of 15 minutes is recommended for the Office and Manufacturing (low) purpose groups less than 5m in height and that have a maximum floor area of any single floor of 1000m^2, or, they contain sprinklers. This is based on the following considerations:

- The recommendations are for life-safety purposes.
- Compartmentation is not required within these buildings.
- The occupants are awake and familiar with the building and will escape before the fire is severe enough to cause structural damage.

However, it is recommended. that a fire alarm system with a L2 level of smoke detection (as specified by BS5839: Part 1) would ensure that the evacuation would be completed without any reliance on structural fire resistance.

15 minute reduction in residential buildings:

A 15-minute reduction to the fire resistance period is recommended for residential buildings with a compartment floor area no greater than 10% of the total floor.

Since the consequence ratings were determined on the basis that failure means complete failure of the entire structure, this is especially conservative for residential buildings where the degree of compartmentation is high and permanent. This means that it is very unlikely that a fire will grow to such an extent that it causes collapse of the entire structure and hence the consequence of failure is less than what is assumed by the consequence ratings in Table 4. Furthermore, it should be remembered that the consequence ratings have also been increased to accommodate the sleeping risk.

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6. CONCLUSIONS

The objectives of the Task Group to derive a new set of fire resistance tables for different building occupancies that can be easily implemented by non specialist fire engineers, have been achieved. This has been carried out in a structured engineering two-stage process based upon a Time Equivalent graphical approach.

The first step involved developing the graphical approach to measuring Time Equivalent and coupling this with a Monte Carlo analysis in order to consider many thousands of fire scenarios for each building occupancy type. The output from this analysis provided a set of cumulative Time Equivalent fire resistance distributions for both sprinklered and non-sprinklered buildings.

The second stage involved using the cumulative time equivalent distributions and developing a risk and consequence approach to structural fire safety. This was achieved by linking the risk to life/evacuation with the height of the building and adjusting the required fire resistance by moving either up a down the cumulative distributions depending upon the building height and type of occupant. During the second stage analysis, it was found necessary to introduce two new height bands to enable the engineering solutions to be aligned more closely with the risk, 11m and 60m.

From the study, two new sets of Tables of Fire Resistance and Occupancy have been developed to cover Sprinklered and Non-Sprinklered buildings. These have been compared with the existing fire resistance tables given in the AD-B. Where a direct comparison can be made the following summarise the proposed changes:

Non-Sprinklered Buildings:

No. of instances remaining unchaged = 12.
No. of instances where there has been an increase = 20.
No. of instances where there has been a reduction = 18.

Main observations:
* The majority of the reductions are in the low rise buildings.
* For dwellings - increase for **all** height categories.

Sprinklered Buildings:

No. of instances remaining unchanged = 15
No. of instances where there has been an increase = 11
No. of instances where there has been a reduction = 16

Main observations:
* Uniform distribution of changes.
* Increase in fire resistance for manufacturing (high hazard)
* Reasonable reduction in fire resistance for installing sprinklers in residential buildings with some still maintaining higher levels than for non-sprinklered premises

The overall approach adopted in the analytical processes has been transparent which allows for adjustments at a later date that can be carried out in a scientific and wholly structured manner. This process can provide the basis of further development of risk-based categories.

7. OTHER CONSIDERATIONS/RECOMMENDATIONS

7.1 Basements

In the discussions within the Task Group, it was agreed that for basements the ventilations conditions are extremely difficult to quantify. The use of the parametric expressions and the calculation of Time equvalent can be fraught with error. For example, if there were only a small amount of ventilation sufficient to allow limited combustion, much of the fuel load would only be volatised. The sudden influx of air as a result of a door opening for example, would create an semi-explosive response rather than one which followed a well defined parametric heating curve.

Since the application of a time equivalent approach at low ventilation conditions is questionable, it was agreed within the Task Group the recommendations for basements should follow those currently given in the AD-B.

CAR PARKS – STILL TO DO ??

Fractile (BS7974)	**Fire Load Density (MJ/m^2 of floor area)**					
	Office	**Hotel**	**Retail**	**Assembly (high - *retail*)**	**Assembly (ordinary - *office*)**	**Assembly (Low - *School*)**
100%*	1200	650	2000	2000	1200	650
95%	760	510	1300	1300	760	450
90%	670	460	1100	1100	670	410
80%	570	400	900	900	570	360
Average	420	310	600	600	420	285

* Value introduced

Values of Fire Load Density for Specific Fractiles (BS7974) used in the Analysis. Table 1a

Fractile (BS7974)	**Fire Load Density (MJ/m^2 of floor area)**			
	Hospital	**Residential**	**Manufact^{rng} (Low)**	**Manufact^{rng} & Storage (High)**
100%*	700	1200	1000	3700
95%	520	970	720	2690
90%	440	920	590	2240
80%	350	870	470	1800
Average	230	780	300	1180

* Value introduced.

Values of Fire Load Density for Specific Fractiles (BS7974) used in the Analysis. Table 1b

Ventilation Parameter	**Occupancy Type**					
	Office	**Hotel**	**Retail**	**Assembly (high - *retail*)**	**Assembly (ordinary - *office*)**	**Assembly (Low - *School*)**
Area (% of Floor Area)	5 to 40 (SD)	10 to 30 (SD)	5 to 40 (SD)	2.5 to 20 (SD)	2.5 to 20 (SD)	2.5 to 20 (SD)
Height (Proportion of Compartment Height)	0.3 to 0.9 (SD)	0.4 to 0.9 (SD)	0.5 to 1.0 (SD)	0.3 to 0.8 (SD)	0.3 to 0.8 (SD)	0.3 to 0.8 (SD)

SD = Square Distribution

Variations in Ventilation Conditions Adopted for each Occupancy. Table 2a

Ventilation Parameter	**Occupancy Type**			
	Hospital	**Residential**	**Manufact^{rng}**	**Manufact^{rng} & Storage**
Area (% of Floor Area)	10 to 30 (SD)	10 to 20 (SD)	2.5 to 20 (SD)	2.5 to 20 (SD)
Height (Proportion of Compartment Height)	0.3 to 0.8 (SD)	0.3 to 0.9 (SD)	0.3 to 0.8 (SD)	0.3 to 0.8 (SD)

SD = Square Distribution

Variations in Ventilation Conditions Adopted for each Occupancy. Table 2b

Geometric Parameter	**Occupancy Type**					
	Office	**Hotel**	**Retail**	**Assembly (high - *retail*)**	**Assembly (ordinary - *office*)**	**Assembly (Low - *School*)**
Floor Area m^2	50 to 1000 (SD)	20 to 60 (SD)	400	400	400	400
Compartment Height m	2.8 to 4.5 (SD)	2.4	4.5 to 7.0 (SD)	3.5 to 6.0 (SD)	3.5 to 6.0 (SD)	3.5 to 6.0 (SD)

SD = Square Distribution.

Variations in Compartment Geometry Adopted for each Occupancy. Table 3a

Geometric Parameter	**Occupancy Type**			
	Hospital	**Residential**	**Manufact^{rng}**	**Manufact^{rng} & Storage**
Floor Area m^2	9 to 750 (SD)	9 to 30 (SD)	400	400
Compartment Height m	2.45 to 4.0 (SD)	2.4	3.5 to 6.0 (SD)	3.5 to 6.0 (SD)

SD = Square Distribution

Variations in Compartment Geometry Adopted for each Occupancy. Table 3b

Height m	**Fractile %**	**Consequence Rating**
0-5	20	1
5-11	46.4	2
11-18	80	3
18-30	92.8	4
30-60	98.2	5
>60	99.6	6
****	100.0	7

Proposed Consequence Rating vs Building Height. Table 4

Occupancy	**Consequence Rating**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Dwelling	51	67	88	102	116	127	151
Hospital	<30	19	32	54	71	84	120
Hotel	<30	26	47	57	69	79	95
Office	<30	31	60	85	114	146	236
Retail	<30	38	68	95	131	174	241
Assembly (low)	<30	28	54	67	83	99	121
Assembly (med)	<30	45	74	99	130	162	240
Assembly (high)	<30	39	87	125	177	227	241
Manufacturing (low)	<30	28	64	88	118	143	151
Manufacturing (high)	58	103	183	241	280	293	300

Outputs from the Cumulative Distribution of Time Equivalent for Non-Sprinklered Occupancies. Table 5

Occupancy	**Consequence Rating**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Dwelling	<15	40	59	67	76	85	104
Hospital	<15	<15	23	29	49	58	80
Hotel	<15	15	23	28	46	52	62
Office	<15	21	32	56	75	92	135
Retail	<15	18	47	66	87	109	149
Assembly (low)	<15	18	27	47	57	66	186
Assembly (med)	<15	22	50	66	84	104	125
Assembly (high)	<15	<30	60	83	114	143	209
Manufacturing (low)	<15	<30	37	59	78	93	111
Manufacturing (high)	26	68	121	173	243	280	300

Outputs from the Cumulative Distribution of Time Equivalent for Sprinklered Occupancies. Table 6

	A	**B**	**C**	**D**
Height to top Floor m	**Awake & Familiar**	**Unfamiliar**	**Asleep**	**Restriction on Means of escape (e.g horizontal evacuation)**
0-5	1	0	+1	+2
5-11	2	0	+1	+2
11-18	3	0	+1	+2
18-30	4	0	+1	+2
30-60	5	0	+1	+2
>60	6	0	+1	+2

Adjustment by Risk. Table 7

Occupancy	Height of Building m					
	0 - 5	5-11	11-18	18-30	30-60	>60
Dwelling	67	88	102	116	127	151
	30	60	60	90	120	120
Hospital	32	54	71	84	120	120
	30*	60	60	90	120	120
Hotel	26	47	57	69	79	95
	30	60	60	90	120	120
Office	<30	31	60	85	114	146
	30	60	60	90	N/P	N/P
Retail	<30	38	68	95	131	174
	60	60	60	90	N/P	N/P
Assembly (low)	<30	28	54	67	83	99
	60	60	60	90	N/P	N/P
Assembly (med)	<30	45	74	99	130	162
	60	60	60	90	N/P	N/P
Assembly (high)	<30	39	87	125	177	227
	60	60	60	90	N/P	N/P
Manufacturing (low)	<30	28	64	88	118	143
	60	90	90	120	N/P	N/P
Manufacturing (high)	58	103	183	241	280	293
	60	90	90	120	N/P	N/P

Non Sprinklered Buildings Adjusted by Risk: Actual Values Compared with the AD-B. Table 8

Notes:

AD-B values in blue font

* increased to 60 minutes in accordance with NHS Code

Occupancy	Building Height m					
	0 - 5	5-11	11-18	18-30	30-60	>60
Dwelling &	**60#**	**90**	**105**	**120**	**135**	**150**
	30	60	60	90	120	120
Hospital	**30***	**60**	**75**	**90**	**120**	**120**
	30*	60	60	90	120	120
Hotel	**30**	**45**	**60**	**75**	**90**	**105**
	30	60	60	90	120	120
Office	**30+**	**30**	**60**	**90**	**120**	**150**
	30	60	60	90	N/P	N/P
Retail	**30**	**45**	**75**	**105**	**135**	**180**
	60	60	60	90	N/P	N/P
Assembly (low)	**30**	**30**	**60**	**75**	**90**	**105**
	60	60	60	90	N/P	N/P
Assembly (med)	**30**	**45**	**75**	**105**	**135**	**180**
	60	60	60	90	N/P	N/P
Assembly (high)	**30**	**45**	**90**	**120**	**180**	**240**
	60	60	60	90	N/P	N/P
Manufacturing (low)	**30+**	**30**	**75**	**90**	**120**	**150**
	60	90	90	120	N/P	N/P
Manufacturing (high)	**60**	**105**	**180**	**240**	**300**	**300**
	60	90	90	120	N/P	N/P

Non Sprinklered Buildings: Proposed Fire Resistance Periods Values Compared with the AD-B. Table 9

Notes:

AD-B values in blue font

+ Reduced to 15minutes when maximum ground floor area is limited to 1000m^2

& 15 minutes reduction when compartment size is limited to 10% of floor area on each floor

Reduced to 30 minutes for single owner occupancy

* Increased to 60 minutes in accordance with NHS Code

Shaded background - phased evacuation fire safety strategy requiring sprinklers (AD-B)

Comparison with AD-B **(Red font: increase in FR, Green font: decrease in FR)**

Occupancy	Building Height m					
	0 -5	**5-11**	**11-18**	**18-30**	**30-60**	**>60**
Dwelling	40	59	67	76	85	104
Sprinklers not considered	30	60	60	90	120	120
Hospital	23	29	49	58	80+	****
Sprinklers not considered	30	60	60	90	120	120
Hotel	15	23	28	46	52	62
Sprinklers not considered	30	60	60	90	120	120
Office	<15	21	32	56	75	92
	30	30	30	60	120	120
Retail	<15	18	47	66	87	109
	30	60	60	60	120	120
Assembly (low)	<15	18	27	47	57	66
	30	60	60	60	120	120
Assembly (med)	<15	22	50	66	84	104
	30	60	60	60	120	120
Assembly (high)	<15	<30	60	83	114	143
	30	60	60	60	120	120
Manufacturing (low)	<15	<30	37	59	78	93
	30	60	60	90	120	120
Manufacturing (high)	26	68	121	173	243	280
	30	60	60	90	120	120

Sprinklered Buildings Adjusted by Risk: Actual Values Compared with the AD-B. Table 10

Notes:

+ 100% value

AD-B values in blue font

Occupancy	**Building Height m**					
	0 -5	**5-11**	**11-18**	**18-30**	**30-60**	**>60**
Dwelling &	**45#**	**60**	**75**	**75**	**90**	**105**
Sprinklers not considered	**30**	**60**	**60**	**90**	**120**	**120**
Hospital	**30**	**30**	**60**	**60**	**90**	**90**
Sprinklers not considered	**30***	**60**	**60**	**90**	**120**	**120**
Hotel	**30**	**30**	**30**	**45**	**60**	**60**
Sprinklers not considered	**30**	**60**	**60**	**90**	**120**	**120**
Office	**15**	**30**	**30**	**60**	**75**	**90**
	30	**30**	**30**	**60**	**120**	**120**
Retail	**30**	**30**	**60**	**75**	**90**	**120**
	30	**60**	**60**	**60**	**120**	**120**
Assembly (low)	**30**	**30**	**30**	**60**	**60**	**75**
	30	**60**	**60**	**60**	**120**	**120**
Assembly (med)	**30**	**30**	**60**	**75**	**90**	**120**
	30	**60**	**60**	**60**	**120**	**120**
Assembly (high)	**30**	**30**	**60**	**90**	**120**	**150**
	30	**60**	**60**	**60**	**120**	**120**
Manufacturing (low)	**15**	**30**	**45**	**60**	**90**	**90**
	30	**60**	**60**	**90**	**120**	**120**
Manufacturing (high)	**30**	**75**	**120**	**180**	**240**	**300**
	30	**60**	**60**	**90**	**120**	**120**

Sprinklered Buildings: Proposed Fire Resistance Periods
Values Compared with the AD-B. Table 11

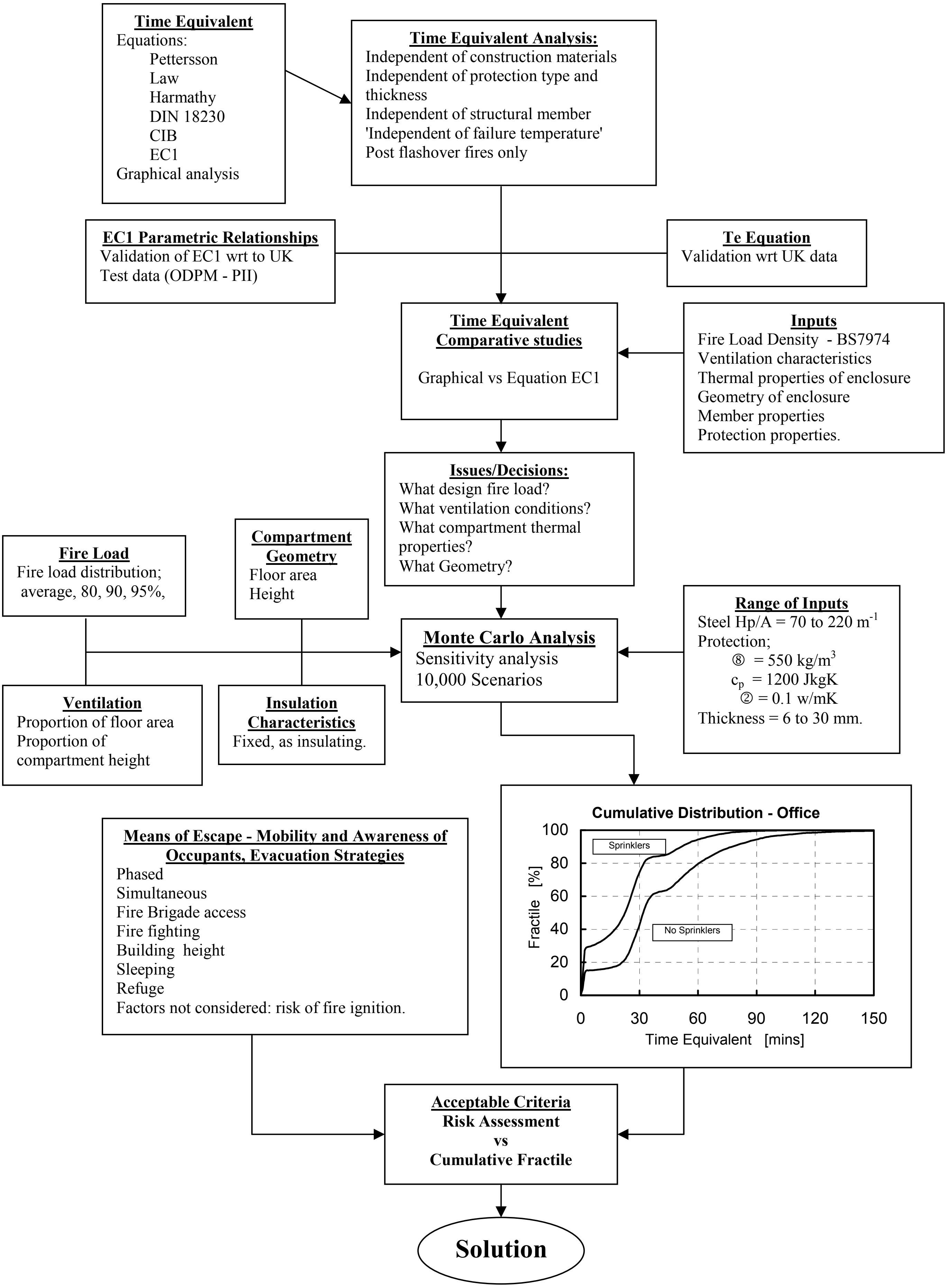
Notes:

AD-B values in blue font

& 15 minutes reduction when compartment size is limited to 10% of floor area on each floor
# Reduced to 30 minutes for single owner occupancy
* Increased to 60 minutes in accordance with NHS Code
Comparison with AD-B **(Red font: increase in FR**, **Green font: decrease in FR)**

ef: FE/37/01/03/O

BS9999: Fire Resistance - Overview of the Analytical Process Figure 1



Time Equivalent
Equations:
- Pettersson
- Law
- Harmathy
- DIN 18230
- CIB
- EC1

Graphical analysis

Time Equivalent Analysis:
Independent of construction materials
Independent of protection type and thickness
Independent of structural member
'Independent of failure temperature'
Post flashover fires only

EC1 Parametric Relationships
Validation of EC1 wrt to UK Test data (ODPM - PII)

Te Equation
Validation wrt UK data

Time Equivalent Comparative studies
Graphical vs Equation EC1

Inputs
Fire Load Density - BS7974
Ventilation characteristics
Thermal properties of enclosure
Geometry of enclosure
Member properties
Protection properties.

Issues/Decisions:
What design fire load?
What ventilation conditions?
What compartment thermal properties?
What Geometry?

Fire Load
Fire load distribution; average, 80, 90, 95%,

Compartment Geometry
Floor area
Height

Monte Carlo Analysis
Sensitivity analysis
10,000 Scenarios

Range of Inputs
Steel Hp/A = 70 to 220 m^{-1}
Protection;
⑧ = 550 kg/m^3
c_p = 1200 JkgK
② = 0.1 w/mK
Thickness = 6 to 30 mm.

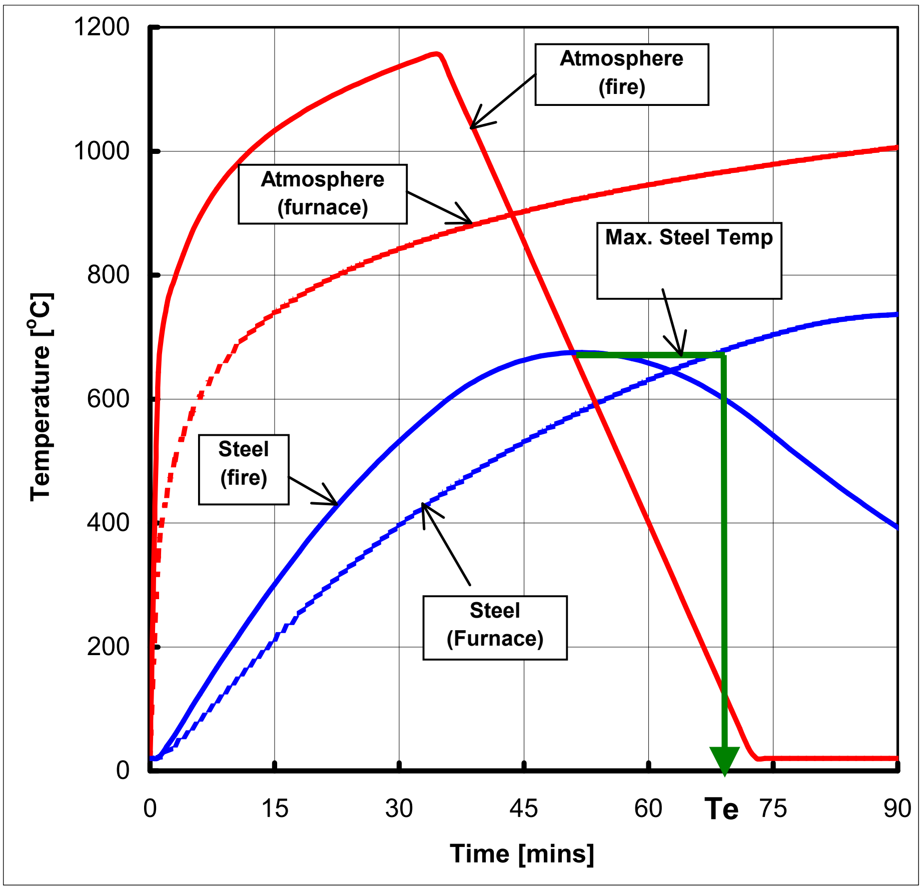
Ventilation
Proportion of floor area
Proportion of compartment height

Insulation Characteristics
Fixed, as insulating.

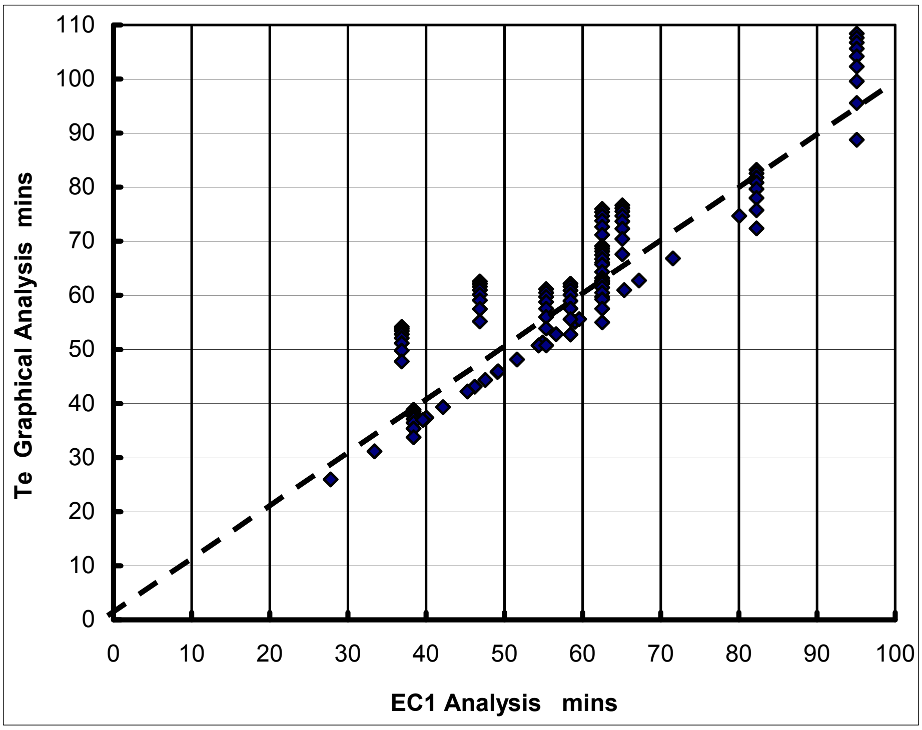
Means of Escape - Mobility and Awareness of Occupants, Evacuation Strategies
Phased
Simultaneous
Fire Brigade access
Fire fighting
Building height
Sleeping
Refuge
Factors not considered: risk of fire ignition.

Acceptable Criteria
Risk Assessment
vs
Cumulative Fractile

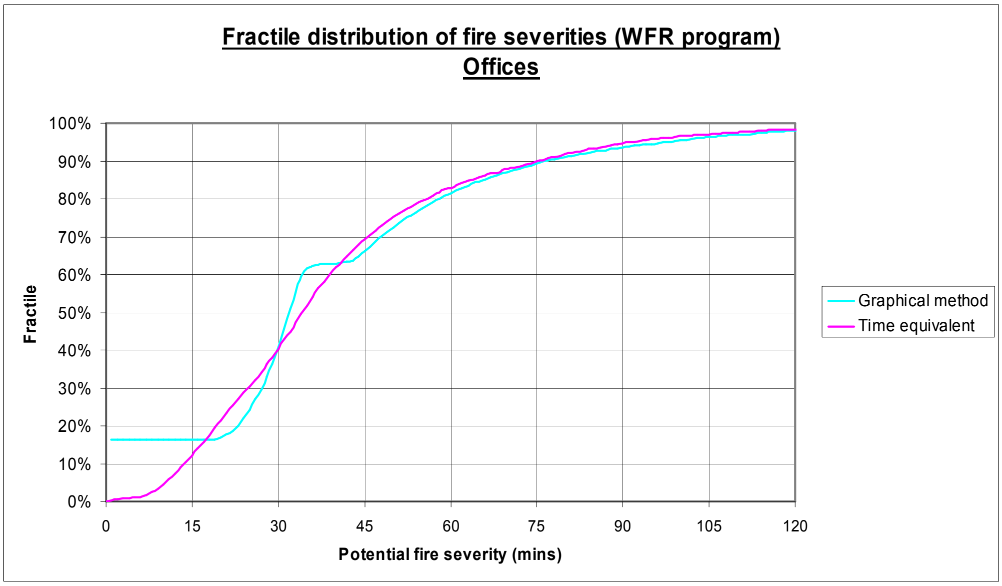
Solution



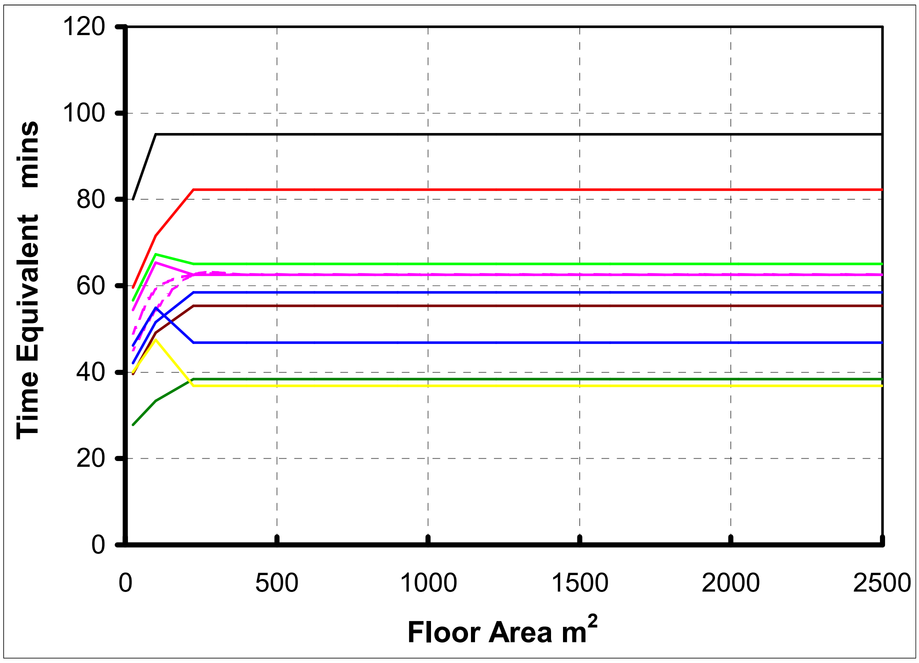
Schematic Representation of the Graphical Time equivalent Analysis   Figure 2



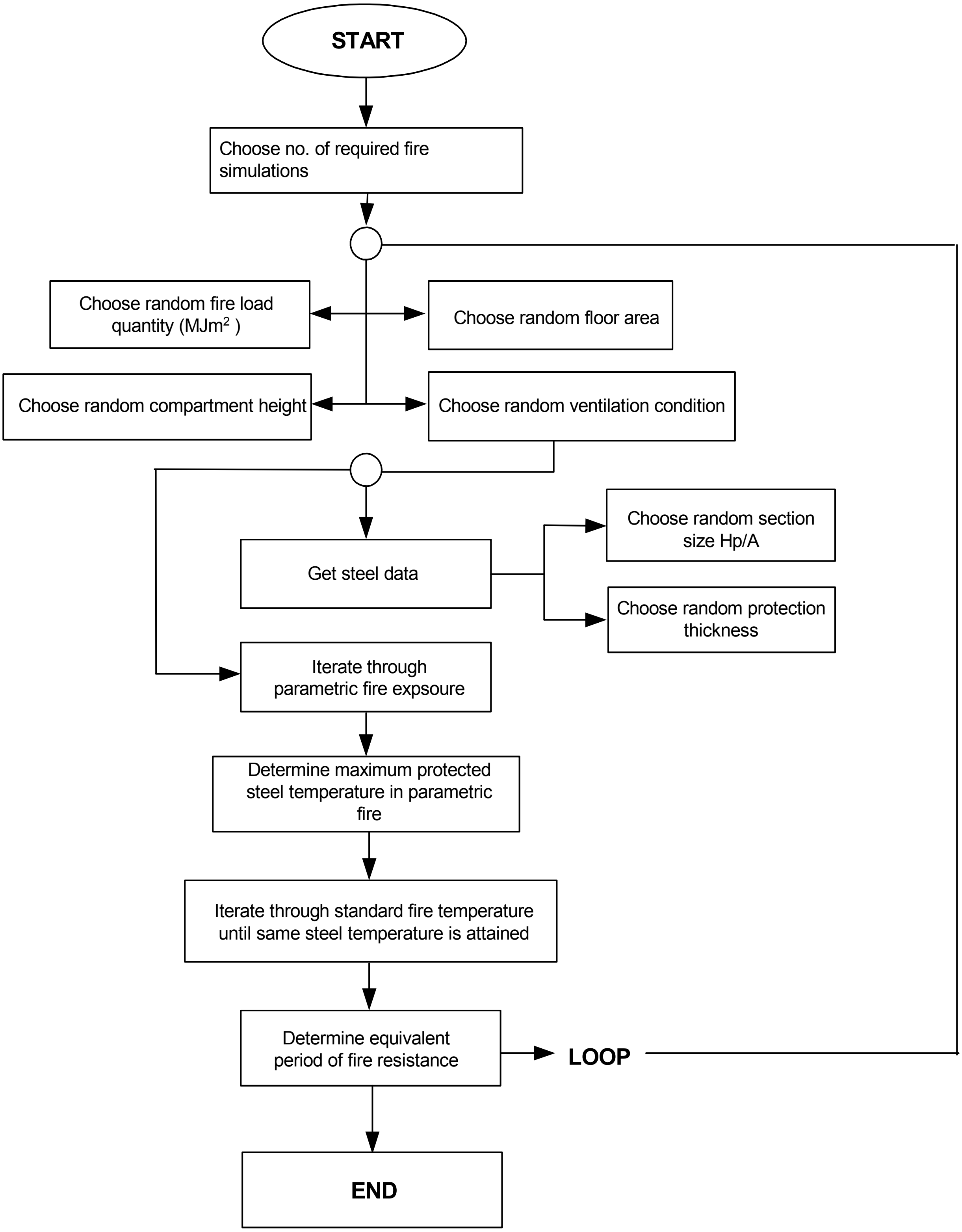
Comparison between Graphical Analysis and Eurocode 1-1-2 for Offices
Figure 3



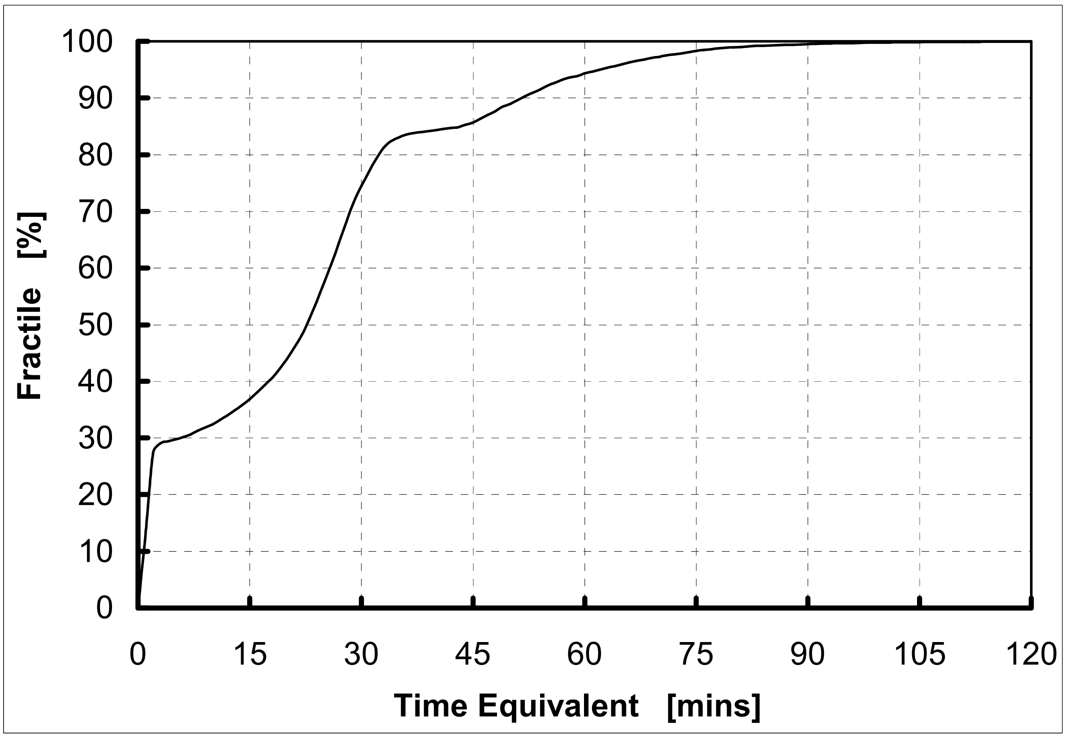
Comparison between the Graphical Method of Time Equivalent and the Eurocode 1-1-2 Equation of the Cumulative Fractile Distribution
Figure 4



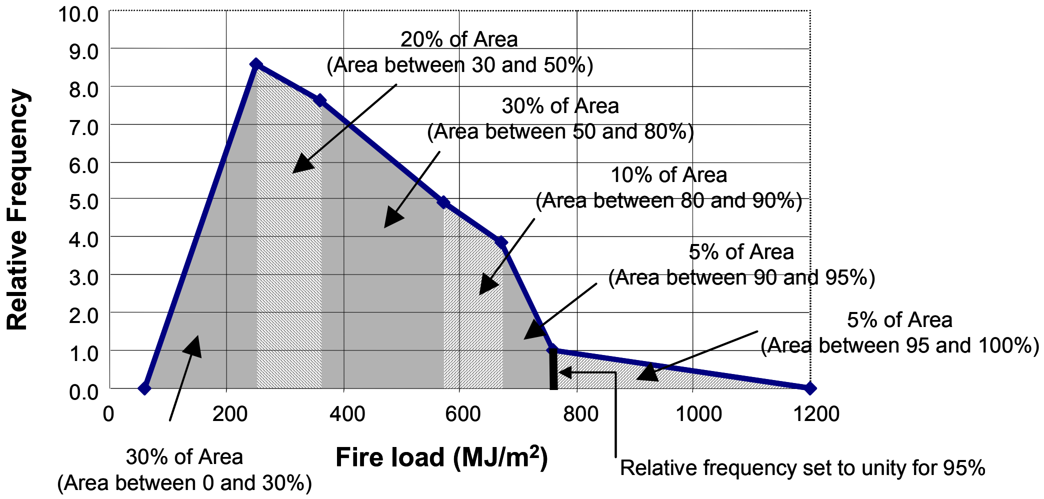
The Influence of Floor Area on Time Equivalent for Different Fire Severities and Compartment Geometries
Figure 5



Monte Carlo Analysis Figure 6



Typical Plot of Cumulative Fractile vs Time Equivalent Figure 7



Method of Constructing the Relative Frequency Diagram Figure 8
(Note: the selected values of 30% and 50% are typical)

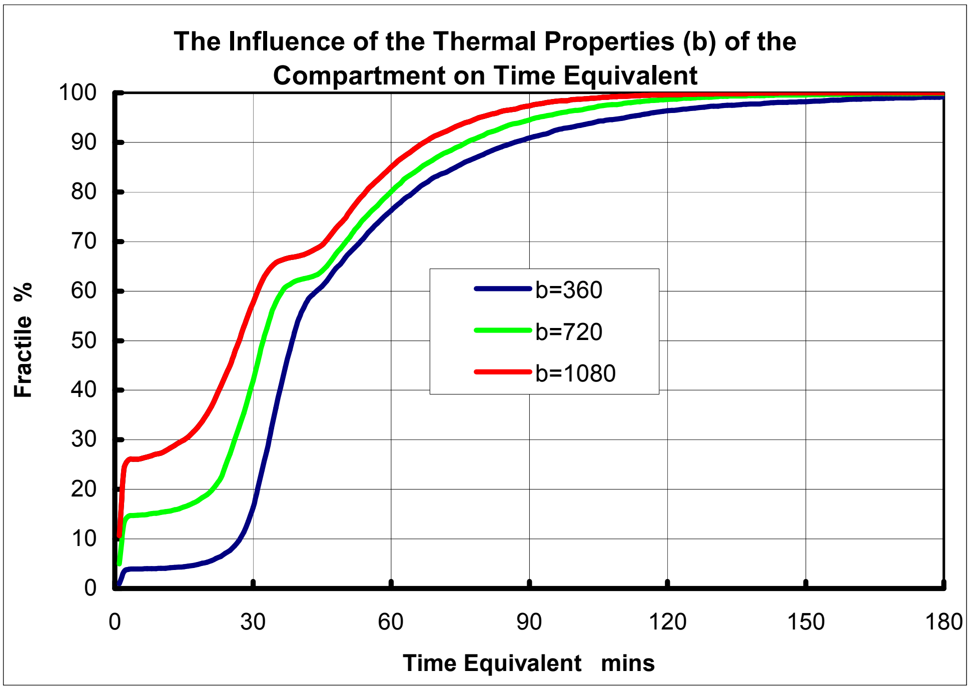


Figure 9

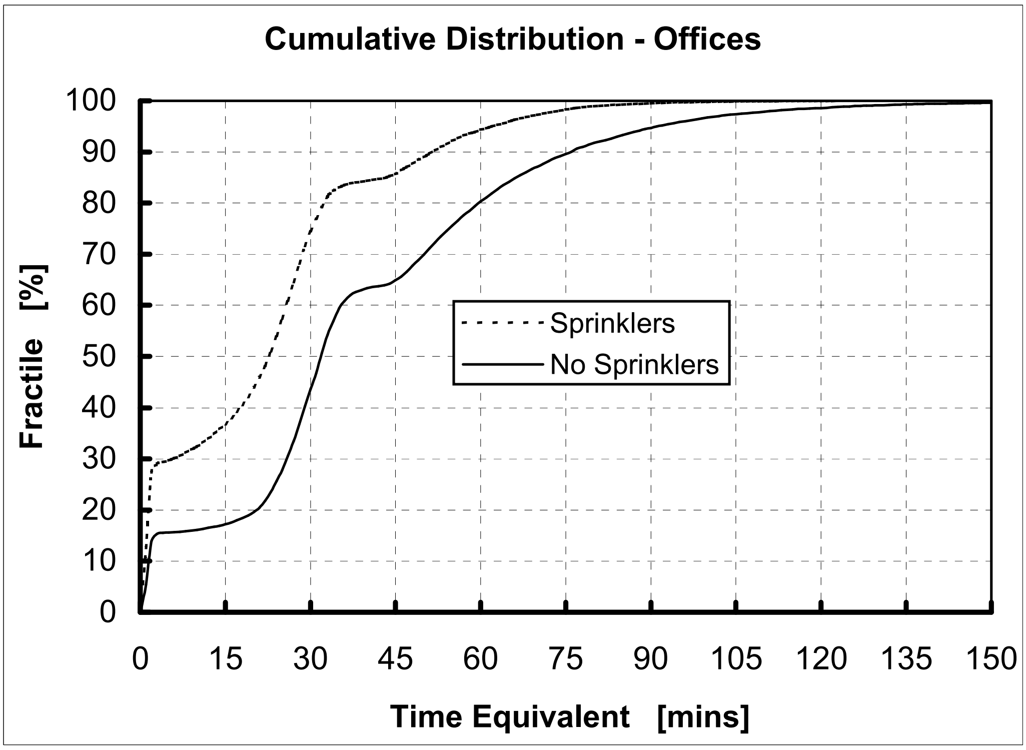


Figure 10

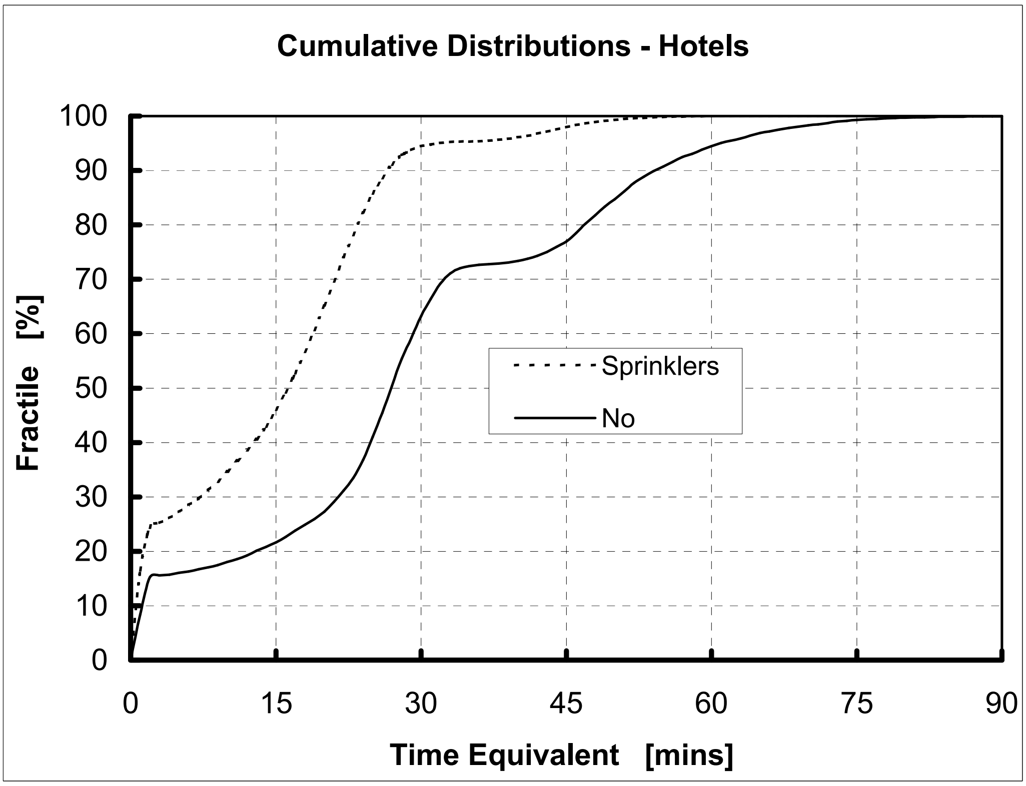


Figure 11

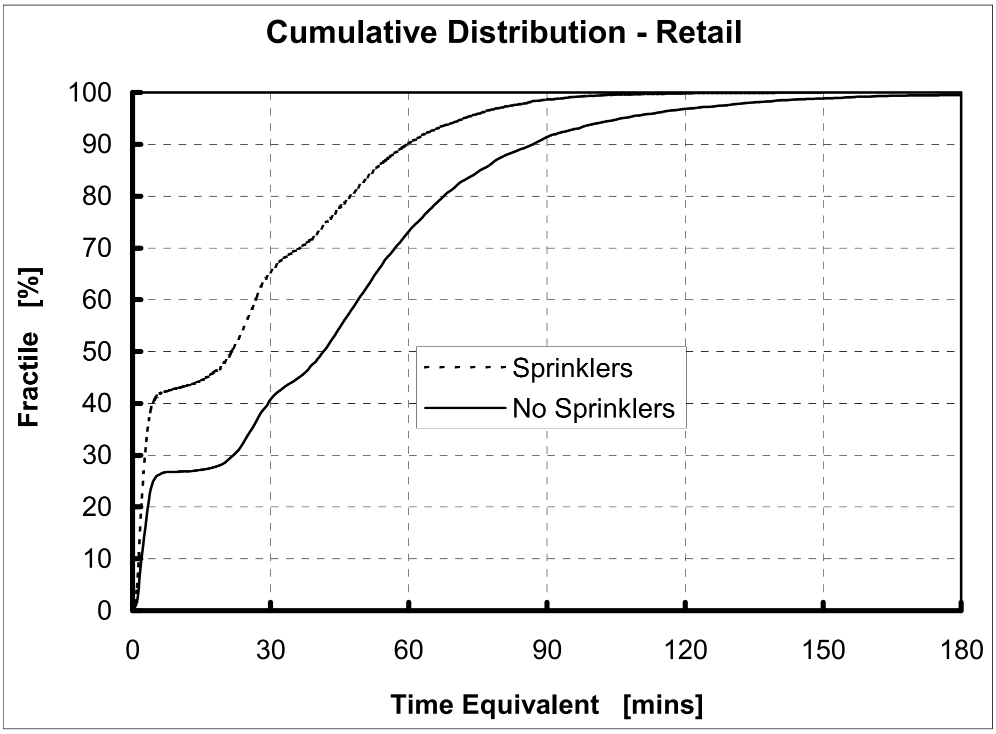


Figure 12

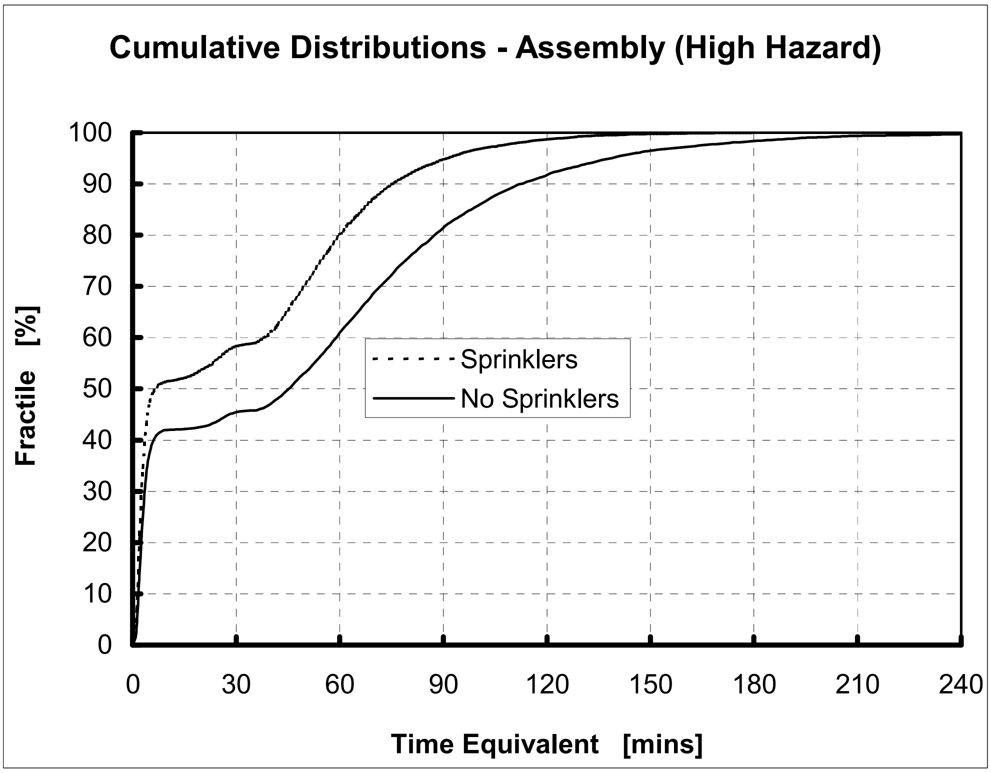


Figure 13

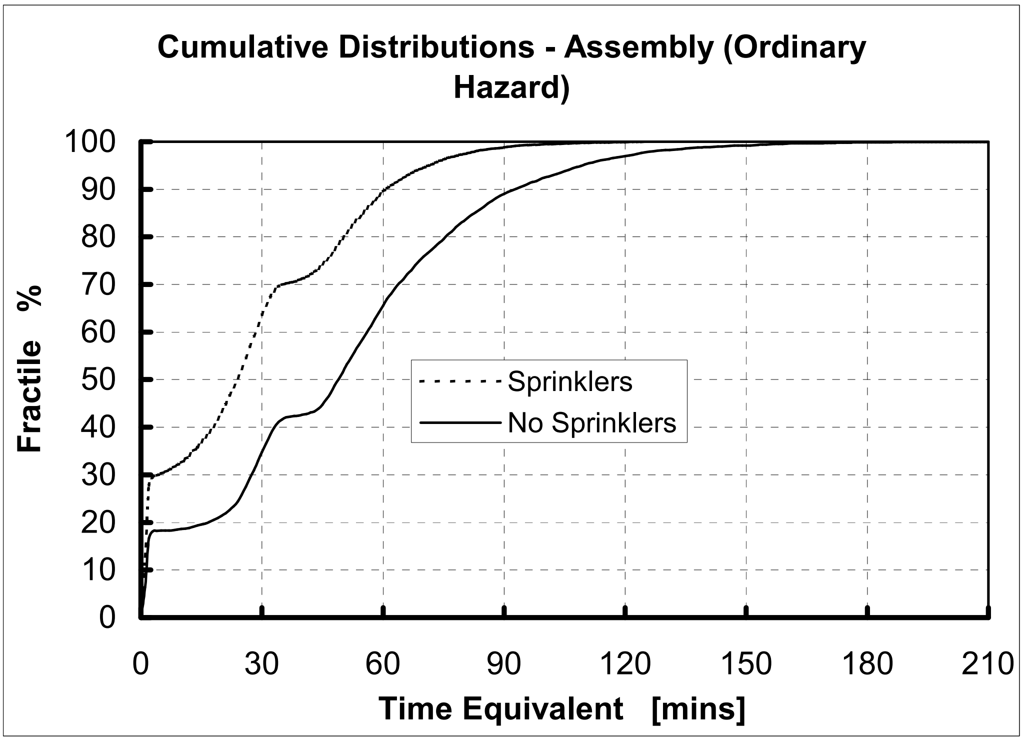


Figure 14

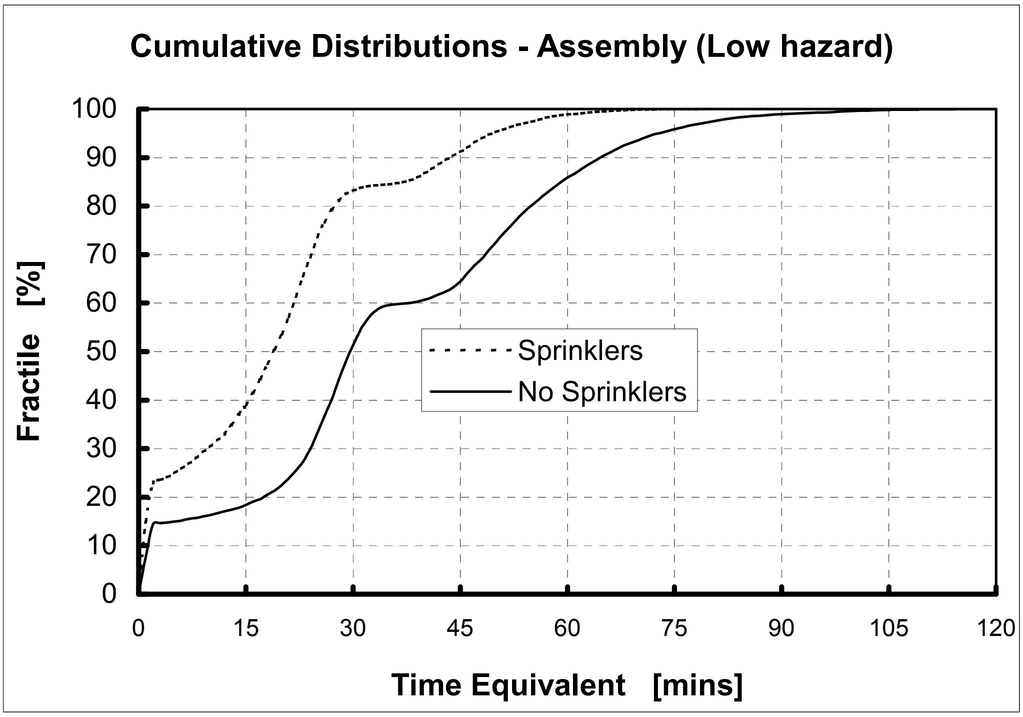


Figure 15

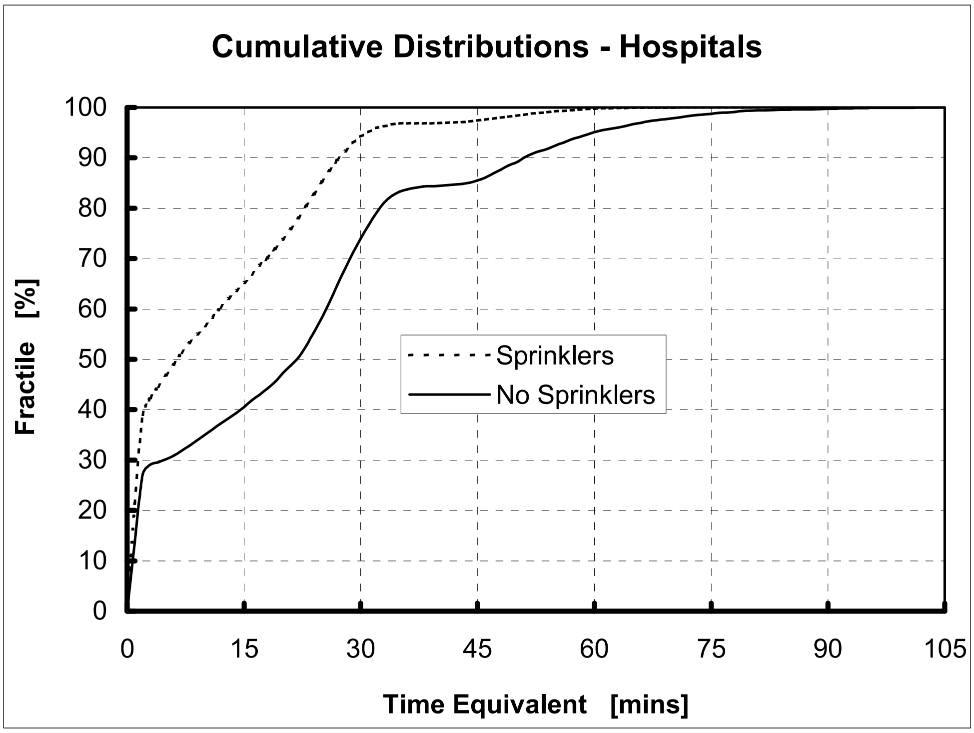


Figure 16

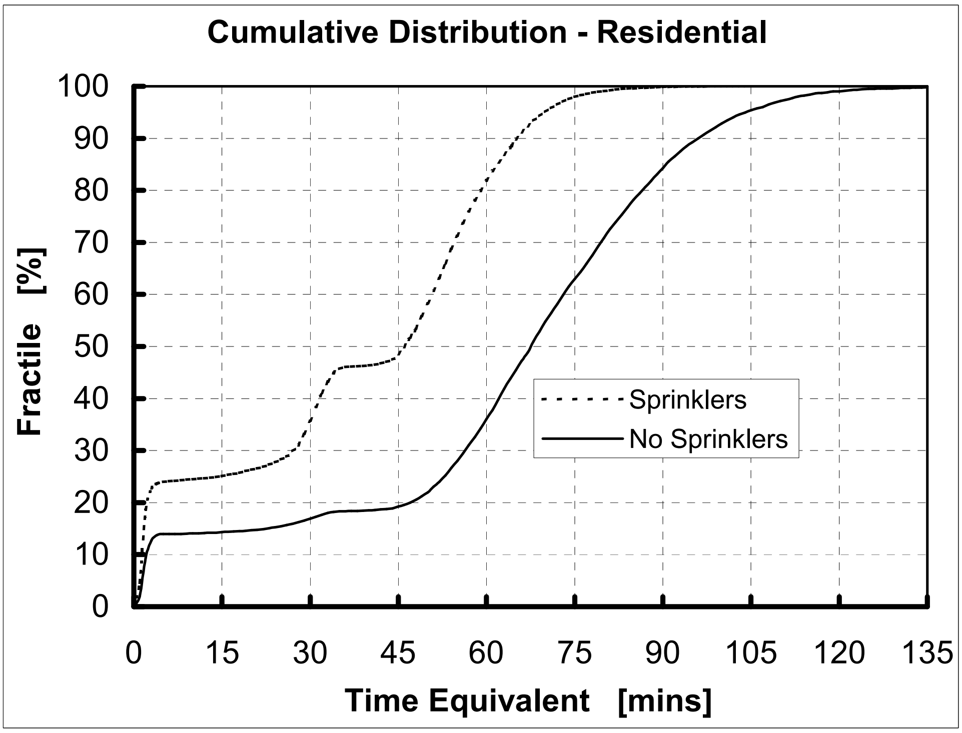


Figure 17

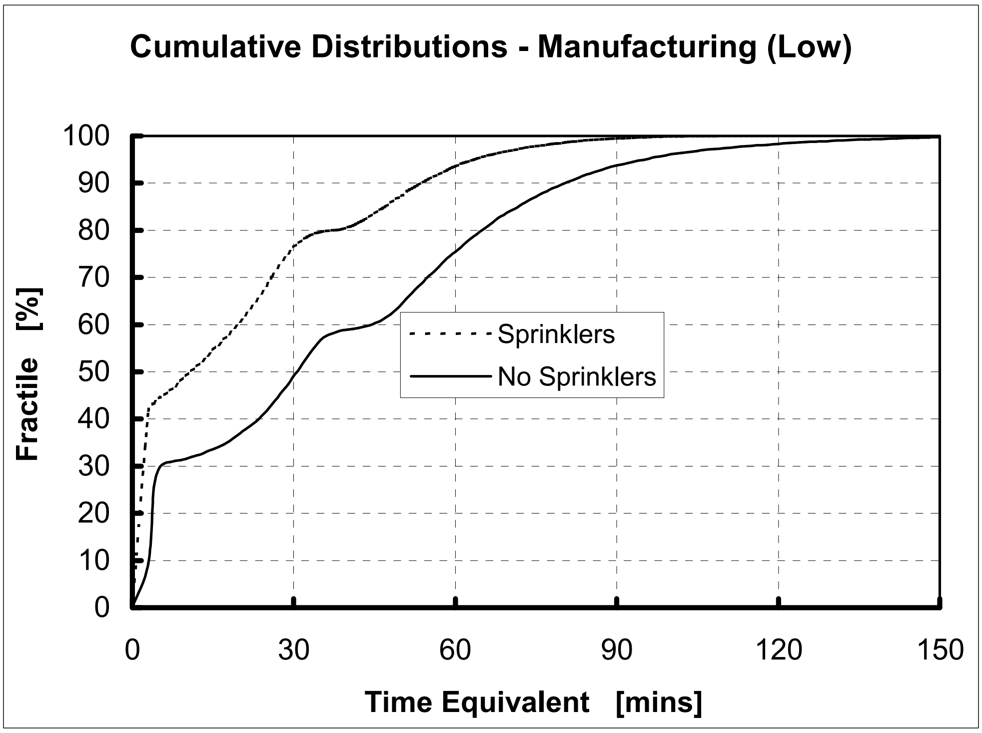


Figure 18

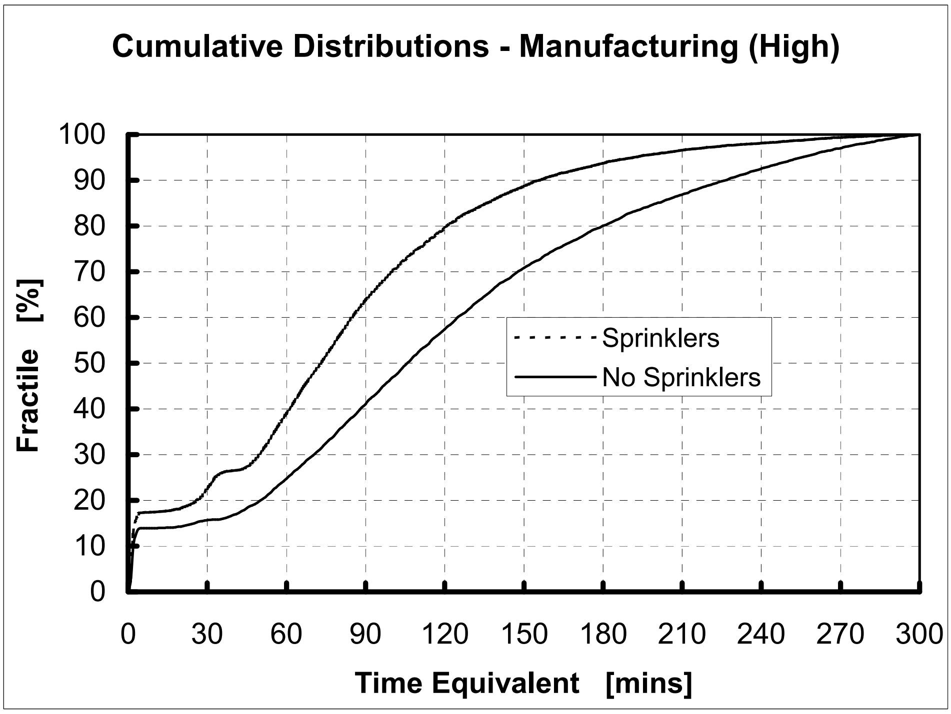


Figure 19