The 9th IIASA-DPRI FORUM on Integrated Disaster Risk Management,
12th October 2009 to 16th October 2009, Kyoto, Japan

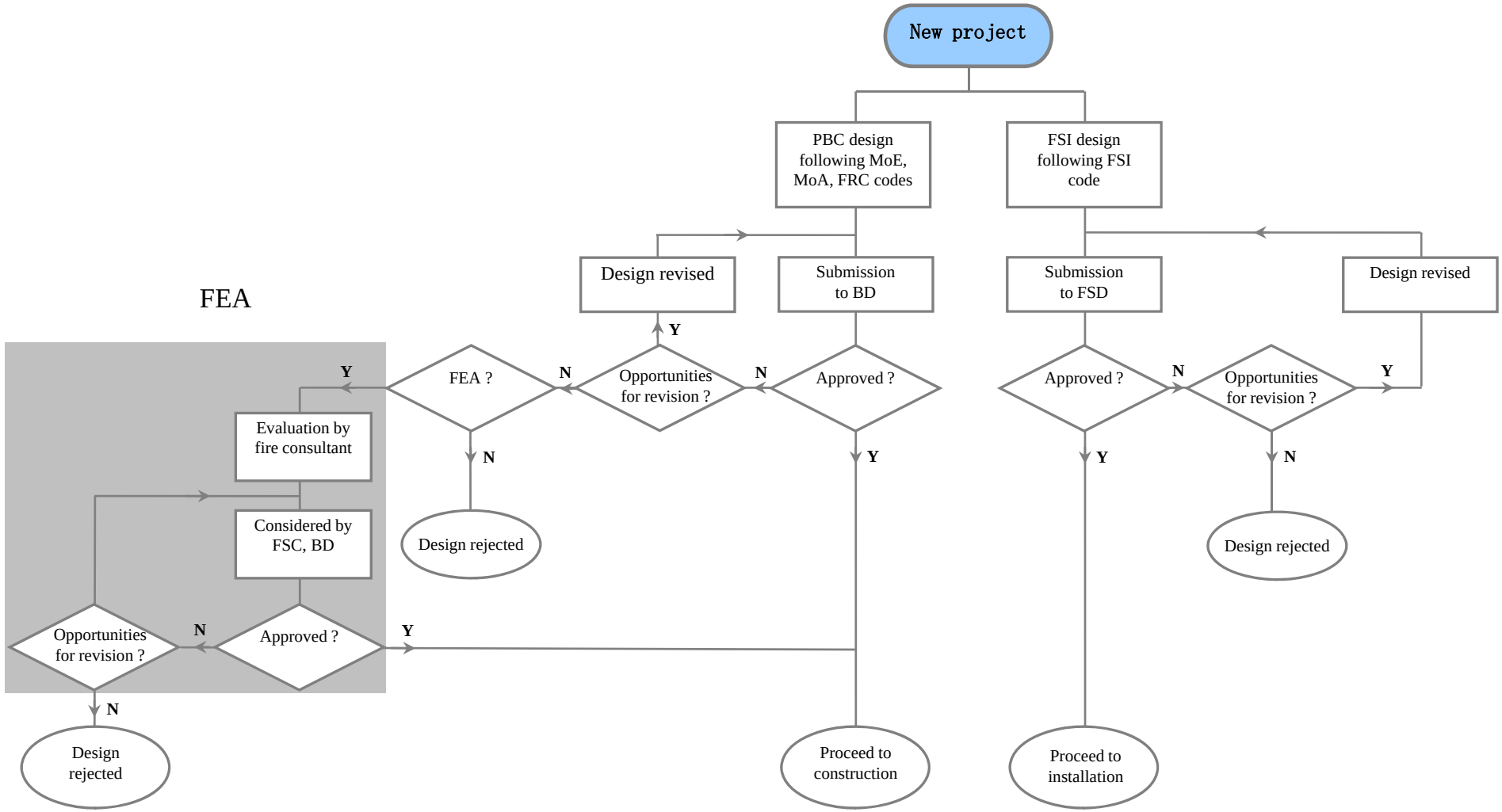
Performance-Based Design for Building Fire Safety in Hong Kong

Dr. N.K. Fong
Area of Strength: Fire Safety Engineering
The Hong Kong Polytechnic University
Hong Kong, China
12th October 2009

- Introduction
- References for fire engineering approach
  - PNAP 204 Guide to Fire Engineering Approach (Practice Note for Authorized Persons and Registered Structural Engineers)
  - SFPE Engineering Guide to Performance-Based Fire Protection : analysis and design of buildings
  - BS 7974:2001 Application of Fire Safety Engineering (FSE) Principles to the Design of Buildings - Code of Practice
- Examples

Introduction

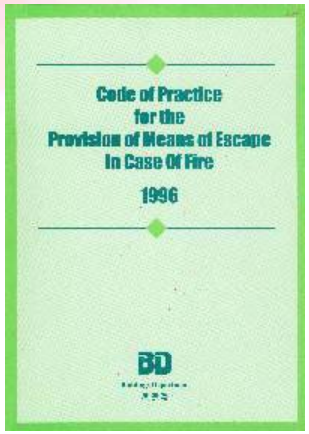
- In Hong Kong, fire safety design in buildings can be based on
  - prescriptive approach
  - fire engineering approach.
- With prescriptive approach, the designer or architect would follow the guidelines laid down in codes of practice, practice notes for authorized persons, circular letters etc.
- For most buildings in Hong Kong, the escape routes design still based on these codes of practice to obtain the “deem to satisfy” provision.



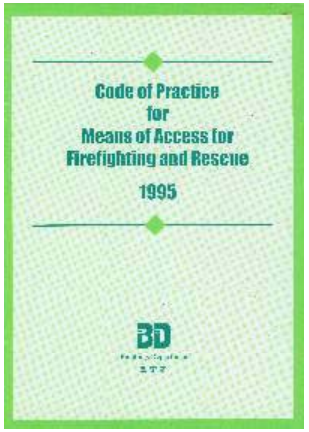
Process for Approving Fire Safety Designs

(Ref: Chow, Architectural Science Review, 2005)

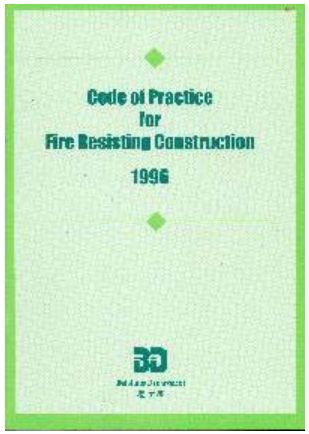
★ **The prescriptive codes, basically on**



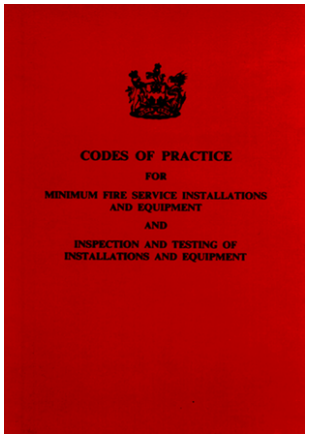
MoE Codes



MoA Codes



FRC Codes

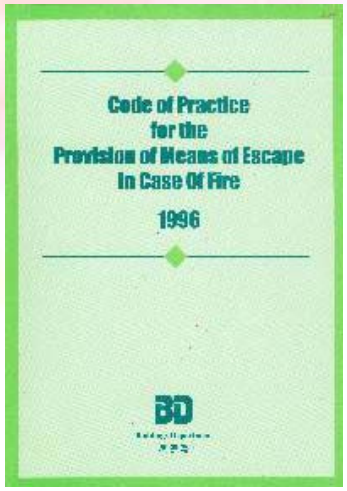


FSI Codes

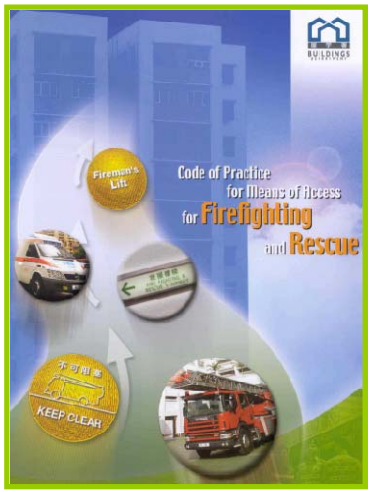
★ **may not be sufficient for providing fire safety in some buildings with special designs.**

Fire Codes in Hong Kong

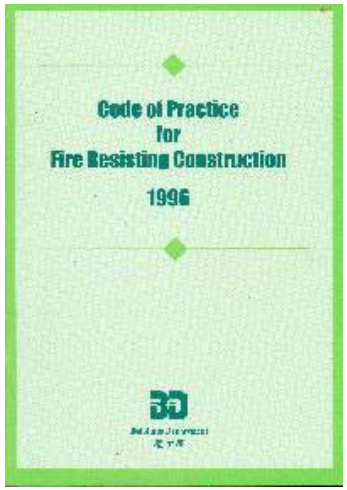
BS5588?



MoE Codes



MoA Codes



FRC Codes

FSI Codes

Research Centre for fire engineering

Local Codes: most of them failed to satisfy the prescriptive codes.

Introduction

- **In the code of practice for the provision of means of escape in case of fire, it provides prescribed figures for the building designer to determine**
  - **the occupant density of the building,**
  - **no. of staircases in both sprinklered and non-sprinklered building,**
  - **discharge values, travel distance and staircase width etc.**

Introduction

- **While in the code of practice for fire resisting construction, it mainly described the provisions for the protection of building and escape route using suitable non-combustible materials which possess a specified fire resistance period for different construction element and resisting the action of fire.**
- **It also stipulates the**
  - **integrity, stability and insulation requirement for the building elements.**
- **It is presumed that design following these codes of practice will provide sufficient protection to the occupants and the building in the case of fire.**

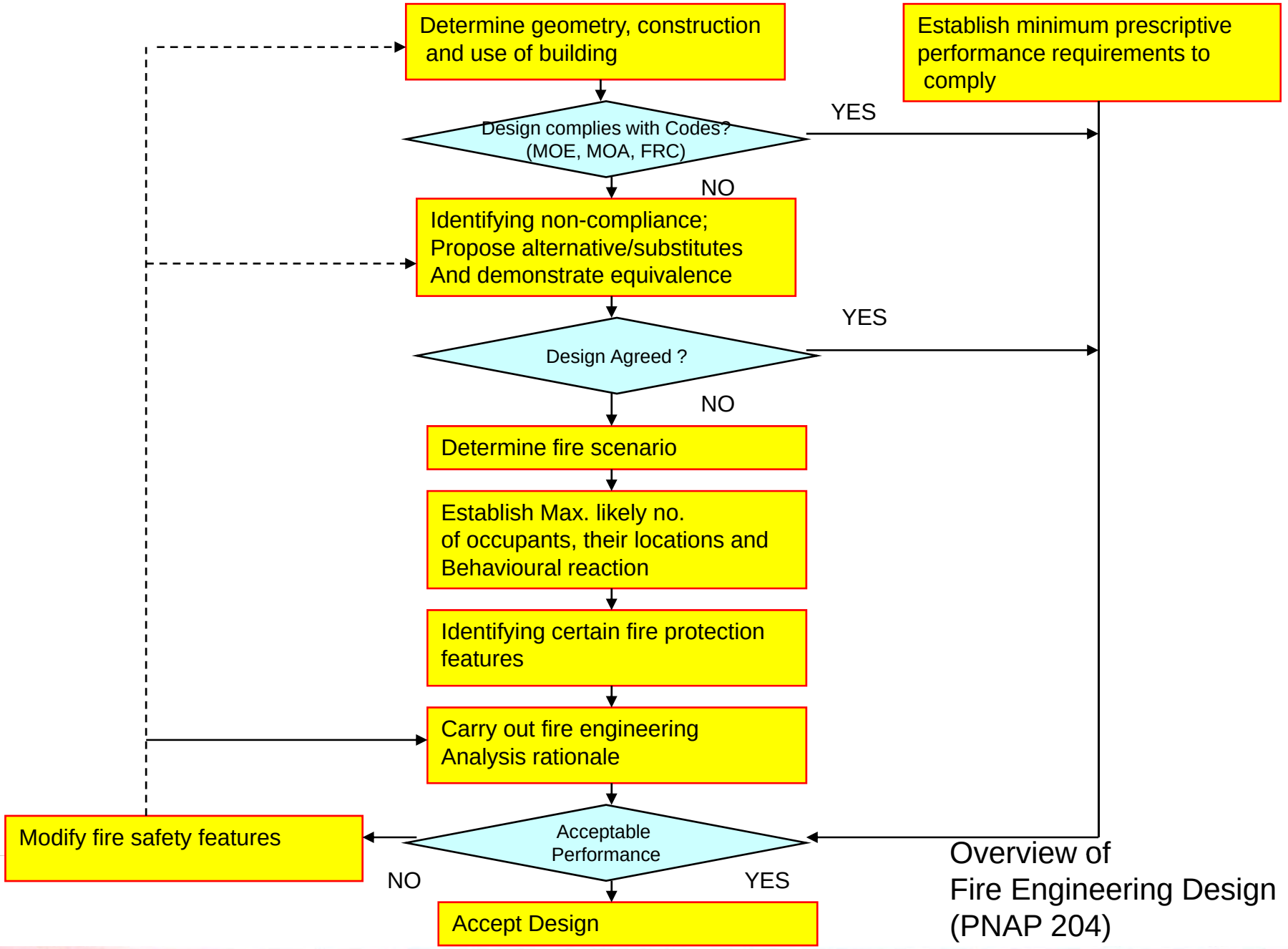
Introduction

- **Under the prescriptive approach, designer or engineers will design the escape route based on the requirement stated in the code of practice without questioning the actual performance of these escape routes and its interaction with the occupants and other building features.**

Introduction

- For buildings with special features such as the Hong Kong Airport, buildings with atrium, the designers / engineers may not be able to provide fire safety design following the requirement prescribed in the codes of practice.
- It is very common for the designers / engineers to adopt the fire engineering approach / performance-based fire engineering design for such buildings.
- Under the fire engineering approach / performance-based fire engineering design, there are no standard figures for the design of escape route, width of staircase etc.
- However, certain principles need to be considered when fire Engineering approach / performance-based fire engineering design is adopted

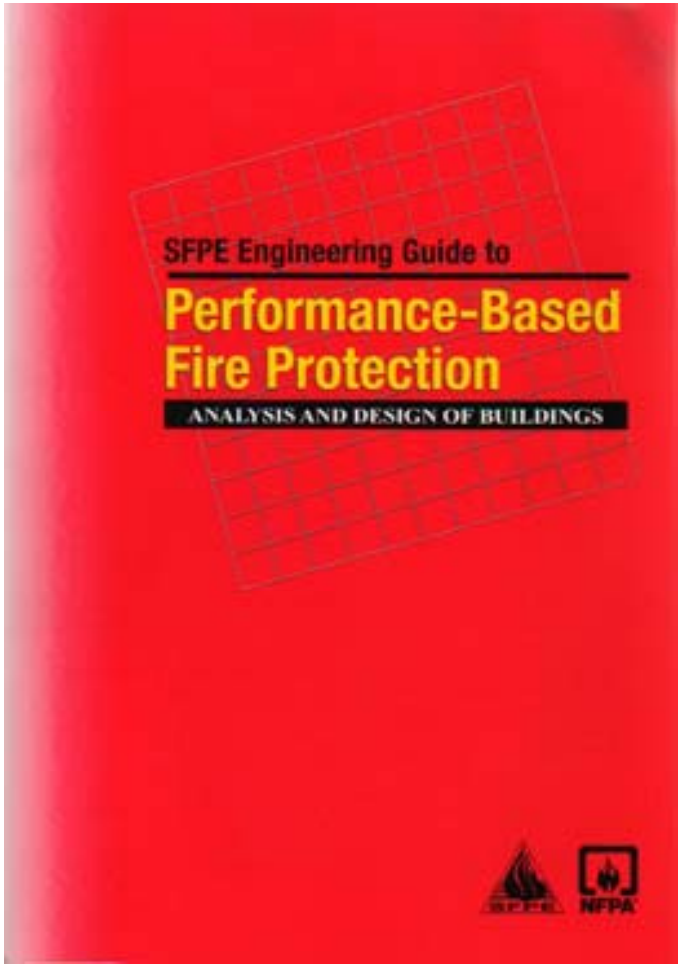
PNAP 204 Guide to Fire Engineering Approach



Overview of
Fire Engineering Design
(PNAP 204)

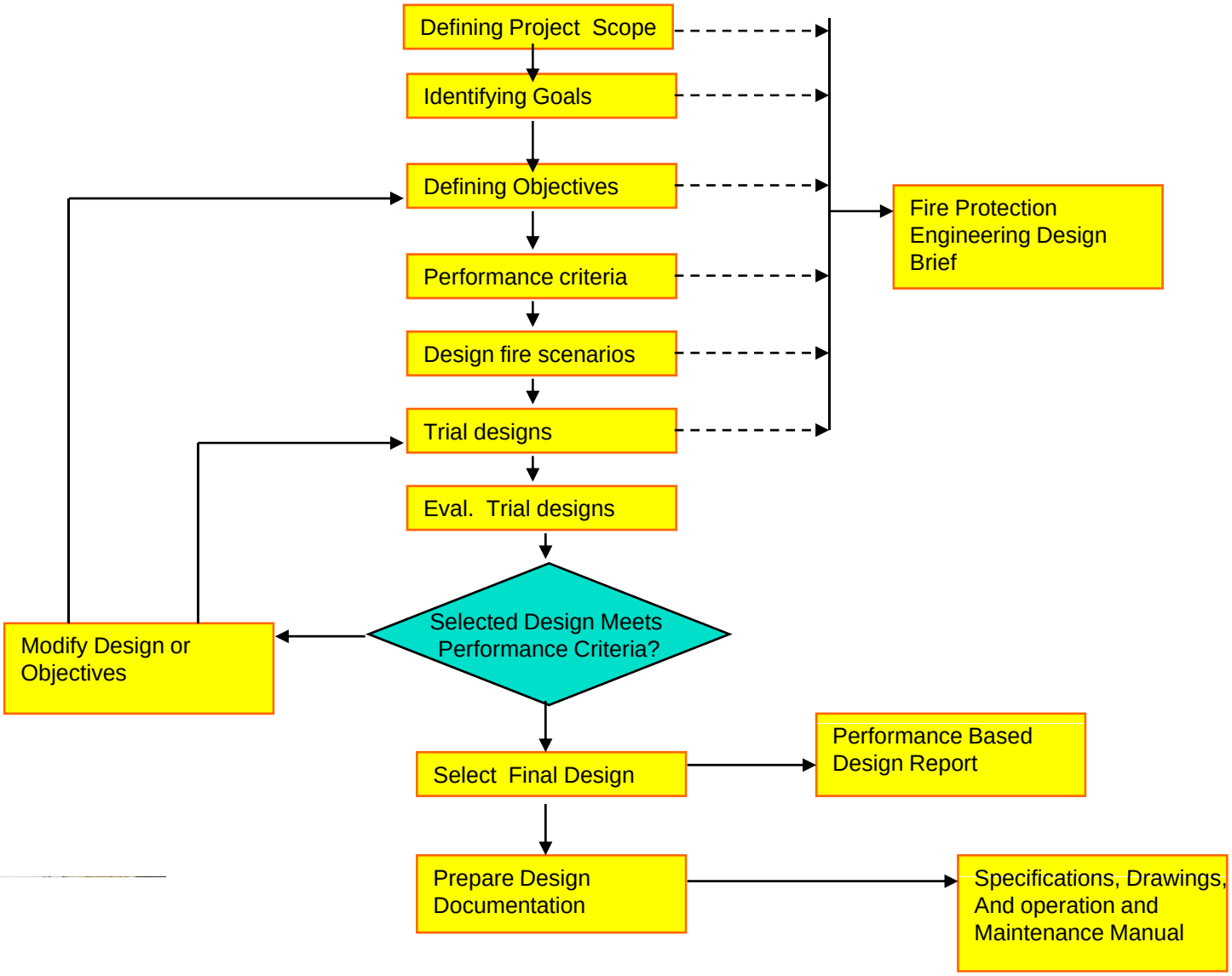
SFPE Engineering Guide to Performance-Based Fire Protection : analysis and design of buildings

Performance-Based Design Process (SFPE)



Extracted from SFPE

Process Flowchart (SFPE)



BS 7974:2001
Application of
Fire Safety Engineering (FSE)
Principles to the Design of Buildings
- Code of Practice

[Originally BS ISO/TR 13387 “Fire Safety Engineering” (1999) Part 1: Application of Fire Performance Concepts to Design Objectives]

British Standard

BS 7974

Application of fire safety engineering principles to the design of buildings -- Code of practice

Published Documents

PD 7974-0	PD 7974-1 (Sub-system 1)	PD 7974-2 (Sub-system 2)	PD 7974-3 (Sub-system 3)	PD 7974-4 (Sub-system 4)	PD 7974-5 (Sub-system 5)	PD 7974-6 (Sub-system 6)	PD 7974-7
Guide to design framework and fire safety engineering procedures	Initiation and development of fire within the enclosure of origin	Spread of smoke and toxic gases within and beyond the enclosure of origin	Structural response and fire spread beyond the enclosure of origin	Detection of fire and activation of fire protection systems	Fire service intervention	Evacuation	Probabilistic risk assessment
• Design approach • QDR • Comparison with criteria • Reporting and presentation	• Design approach • Acceptance criteria • Analysis • Data • References						

Extracted from BS 7974

2-Step Process

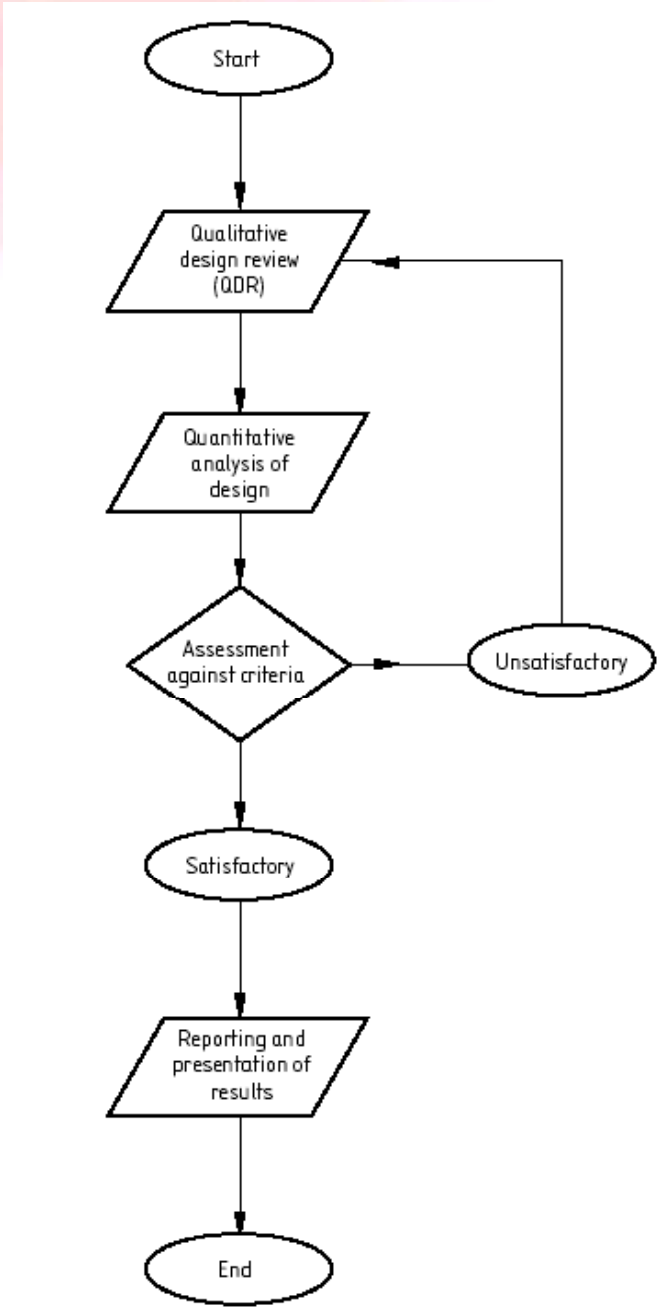


Figure 2 — Basic fire safety engineering process

Extracted from BS 7974

Procedure for undertaking the QDR

- The following steps should be taken when conducting the QDR:
  - Step 1: review the architectural design of the building
  - Step 2: establish the fire safety objectives
  - Step 3:identify fire hazards and possible consequences
  - Step 4: establish trial fire safety designs
  - Step 5: identify acceptance criteria and methods of analysis
  - Step 6: establish fire scenarios for analysis

Components of Step 1: Review the architectural design of the building

- a) building characterization
  - i.e. the layout and geometry of the building, details of the construction, the nature and extent of the loads acting on the structure (e.g. dead loads and imposed loads) and the degree of fire loading present
- b) environmental influences
  - such as wind and snow, which influence fire safety design through their effect on structural load levels, smoke ventilation systems and the nature of external flame envelopes issuing from the windows of the building
- c) occupant characterization
  - i.e the type of occupancy, the building population and its distribution, the likelihood of the fire alarm being raised manually, the type of fire detection and alarm system
- d) management of fire safety
  - i.e. the likely extent and nature of management in the building.

Components of Step 5: Identification of Acceptance Criteria

- **Criteria against which the adequacy of a design can be judged using data determined by one or more of the following methods:**
  - **deterministic (including, when appropriate, safety factors);**
  - **probabilistic (risk-based);**
  - **comparative criteria;**
  - **financial criteria.**

Components of Step 6 : Establish fire scenarios for analysis

- The characterization of a fire scenario for analysis purposes should include a description of the following, where appropriate:
  - type of fire
  - internal ventilation conditions
  - external ventilation conditions
  - performance of each of the safety measures
  - type, size and location of the ignition source
  - distribution and type of fuel
  - fire load density
  - fire suppression
  - state of doors
  - breakage of windows
  - building ventilation system.

Components of Step 6 : Establish fire scenarios for analysis

- Design fires
- To evaluate the effects of a developing fire one or more design fires on which to base the analysis should usually be defined.
- A design fire can be characterized in terms of:
  - heat release rate
  - toxic species production rate
  - smoke production rate
  - fire size (including flame length)
  - time to key events, e.g. flashover

Components of Step 6 : Establish fire scenarios for analysis

- A more complete description of a design fire may include one or all of the following phases:
  - a) *incipient phase*:
    - characterized by a variety of combustion processes which may be smouldering, flaming or radiant;
  - b) *growth phase*:
    - covering the fire propagation period up to flashover (if appropriate) or full fuel involvement;
  - c) *fully developed phase*:
    - characterized by substantially steady burning rates, may occur in ventilation or fuel bed controlled fires;
  - d) *decay phase*:
    - covering the period of declining fire severity;
  - e) *extinction*:
    - when there is no more energy being released.

Quantitative Analysis

- To simplify the evaluation of the fire safety design, the fire safety engineering process should be further broken down into six sub-systems (SS).
- The sub-systems can be used individually to address specific issues or together to address all of the main aspects of fire safety.

Quantitative Analysis

- The sub-systems are as follows:
  - **Sub-system 1:**
    - **initiation and development of fire within enclosure of origin (PD 7974-1)**
  - **Sub-system 2:**
    - **spread of smoke and toxic gases within and beyond enclosure of origin (PD 7974-2)**
  - **Sub-system 3:**
    - **structural response and fire spread beyond enclosure of origin (PD 7974-3)**
  - **Sub-system 4:**
    - **detection and activation of fire protection systems (PD 7974-4)**
  - **Sub-system 5:**
    - **fire service intervention (PD 7974-5)**
  - **Sub-system 6:**
    - **evacuation (PD 7974-6)**

SS1: Initiation and development of fire within the enclosure of origin (see PD 7974-1)

- SS1
  - provides guidance on evaluating fire growth and/or size within the enclosure taking into account the four main stages of fire development:
    - pre-flashover (including early growth and development);
    - flashover;
    - fully developed fire (where all the fuel is burning);
    - decay.

SS1: Initiation and development of fire within the enclosure of origin (see PD 7974-1)

- Given the information in PD 7974-0, it is then possible to calculate a number of parameters, which include:
  - heat release rate;
  - mass production rate of smoke;
  - mass production rate of fire effluents (e.g. CO);
  - flame size and temperature;
  - temperature within enclosure;
  - time to flashover;
  - area of fire involvement.

SS1: Design fires

- Following identification of the design fire scenarios, it is necessary to describe the assumed characteristics of the fire on which the scenario quantification will be based.
  - These assumed fire characteristics are referred to as “the design fire”.
- The design fire
  - needs to be appropriate to the objectives of the fire safety engineering task.
  - For example, if the objective is to evaluate the smoke control system, a design fire should be selected that challenges the system.

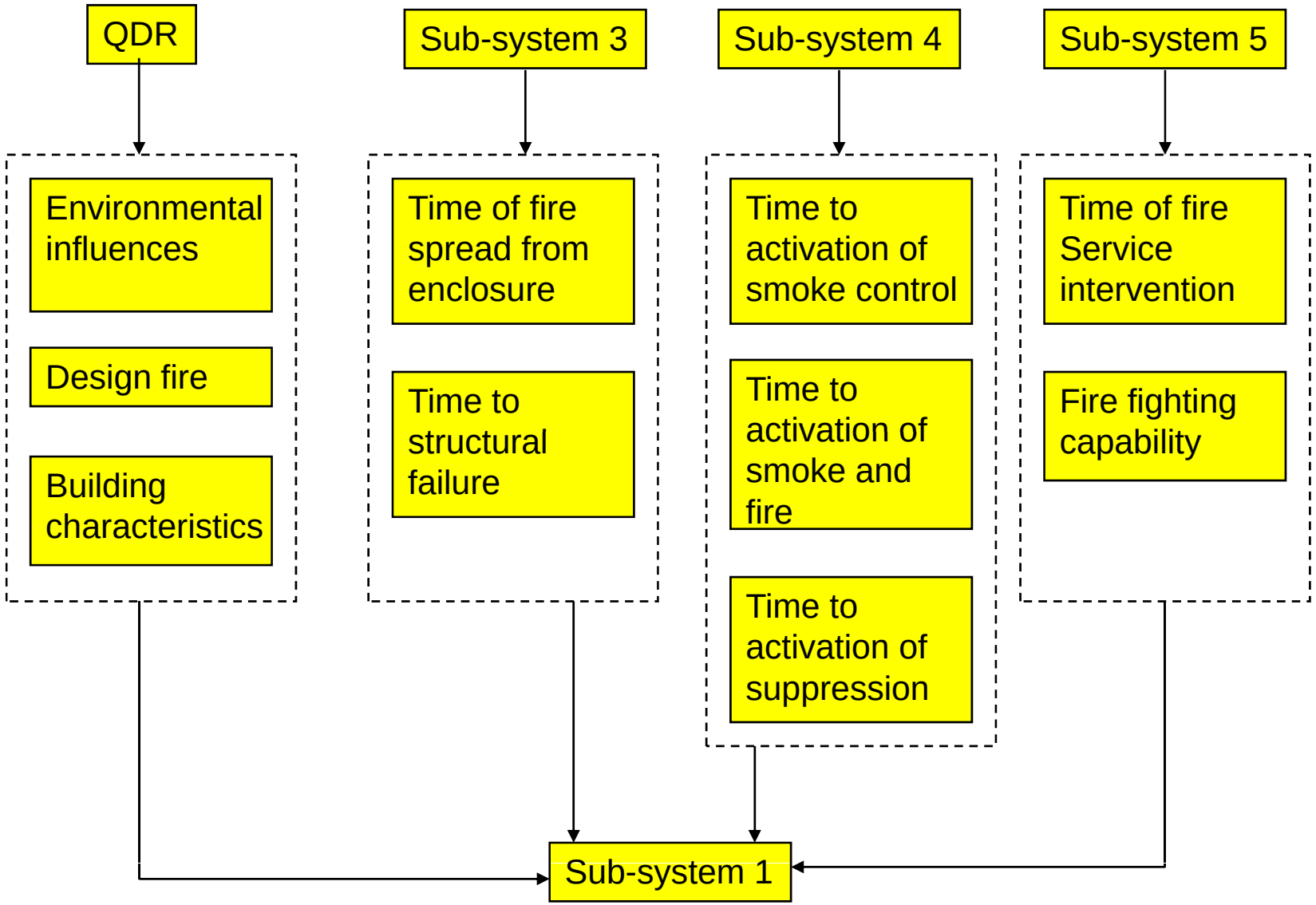
SS1: Design fires

- Design fire
  - unlikely to occur in practice.
- Actual fires
  - likely to be less severe and will not necessary follow the specified design curve, such as a particular heat release curve.
- The design fire quantification process
  - should result in a design profile that is conservative.

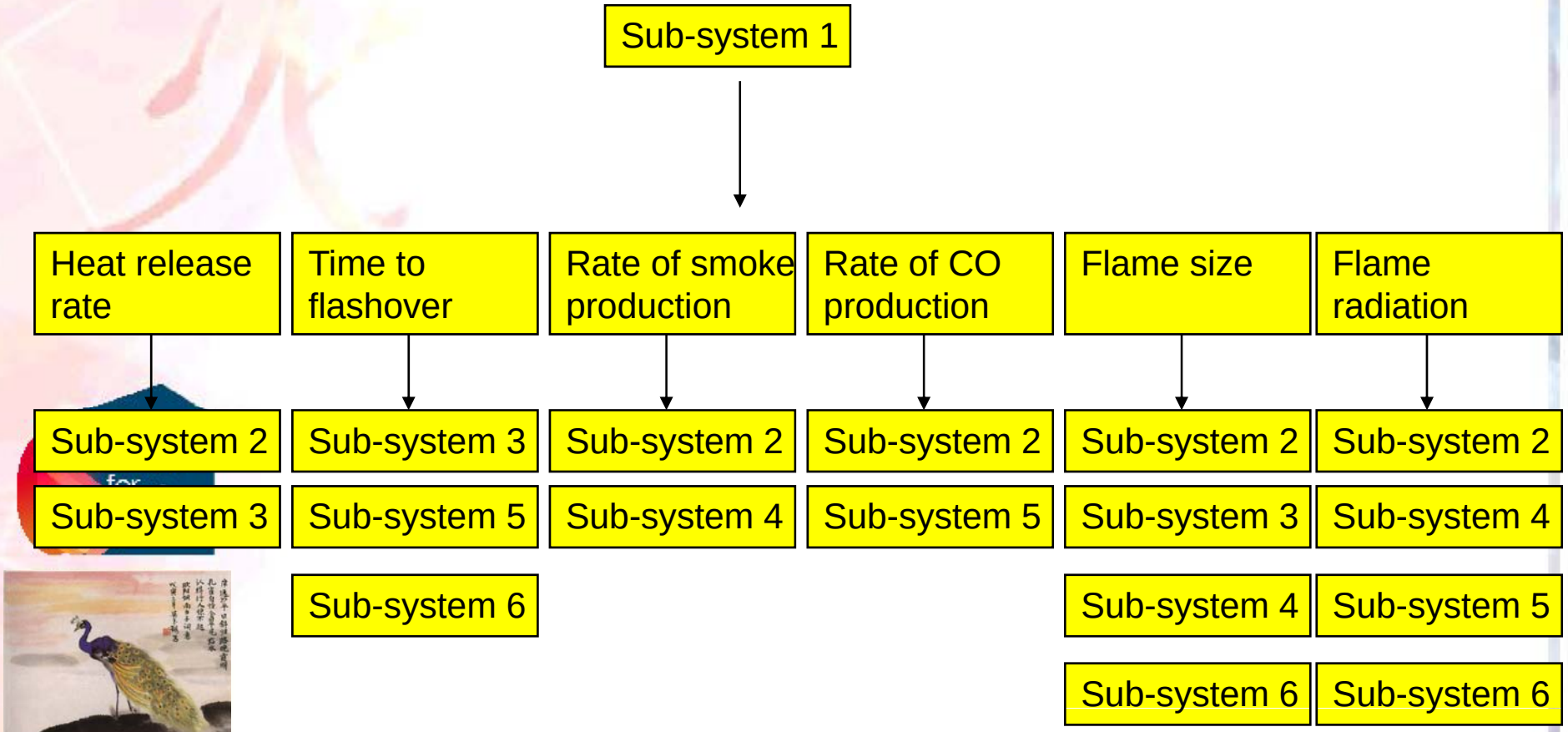
Pre-flashover design fires

- t^2 fires
- Smouldering fires
- Burning objects
- Prescribed fires

SS1: Input


QDR
Sub-system 3
Sub-system 4
Sub-system 5
Environmental influences
Design fire
Building characteristics
Time of fire spread from enclosure
Time to structural failure
Time to activation of smoke control
Time to activation of smoke and fire
Time to activation of suppression
Time of fire Service intervention
Fire fighting capability
Sub-system 1

SS1: output


Sub-system 1
Heat release rate
Time to flashover
Rate of smoke production
Rate of CO production
Flame size
Flame radiation
Sub-system 2
Sub-system 3
Sub-system 2
Sub-system 2
Sub-system 2
Sub-system 2
Sub-system 3
Sub-system 5
Sub-system 4
Sub-system 5
Sub-system 3
Sub-system 4
Sub-system 6
Sub-system 4
Sub-system 5
Sub-system 6
Sub-system 6

SS2: Spread of smoke and toxic gases within and beyond the enclosure of origin (see PD 7974-2)

- SS2 provides guidance by which the following may be evaluated:
  - the spread of smoke and toxic gases within and beyond the enclosure of fire origin;
  - the characteristics of the smoke and the toxic gases at the location of interest.

SS2: analysis of smoke and toxic gases

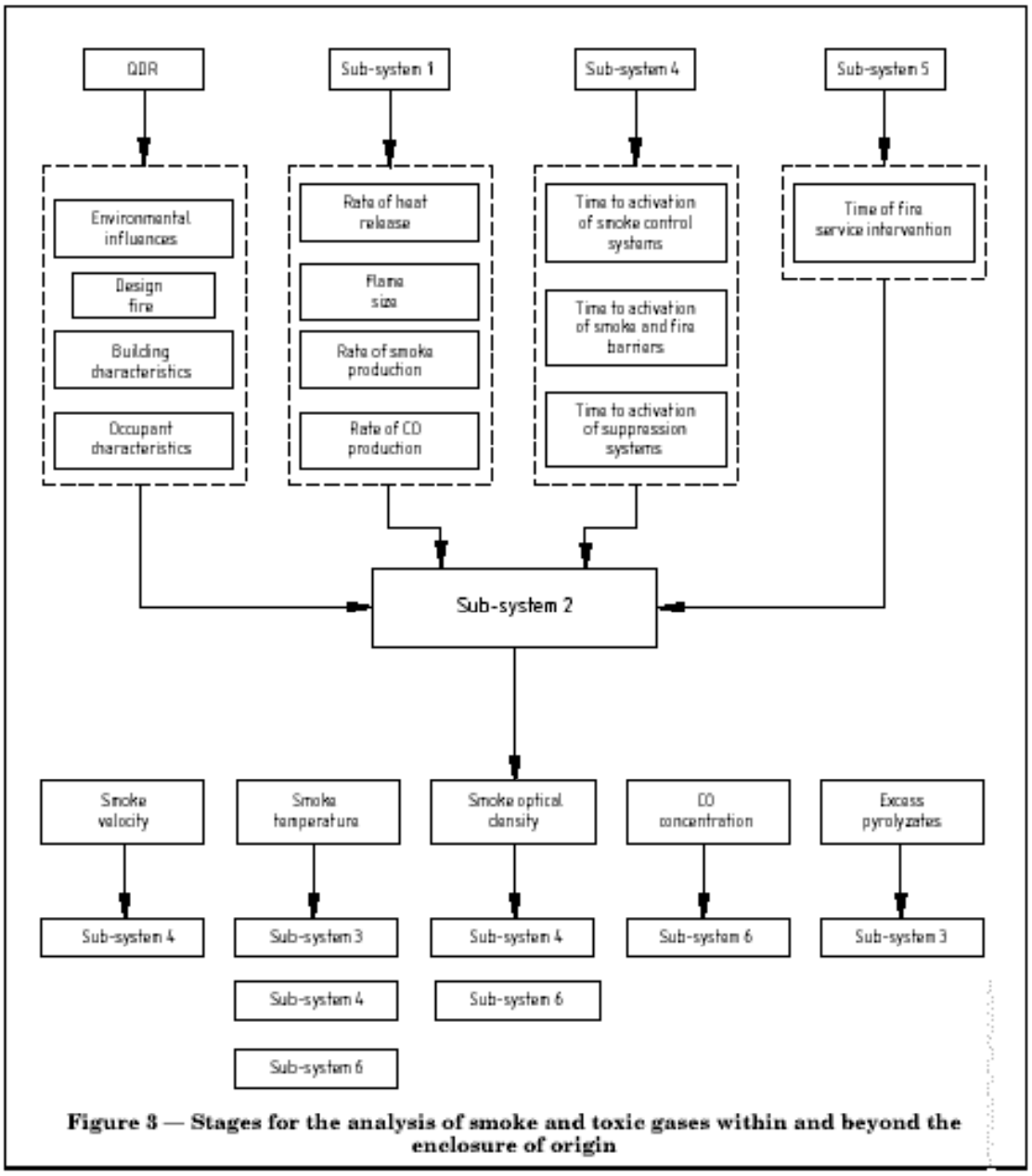


Figure 3 — Stages for the analysis of smoke and toxic gases within and beyond the enclosure of origin

Extracted from BS 7974

SS3: Structural response and fire spread beyond the enclosure of origin (see PD 7974-3)

- SS3 provides guidance so that the following can be evaluated:
  - the fire severity
    - in terms of temperature and heat flux within the enclosure; and
  - the ability of the elements forming the enclosure, directly or in part, to withstand exposure to the prevailing fire severity.

SS3: Structural response and fire spread beyond the enclosure of origin (see PD 7974-3)

Extracted from BS 7974

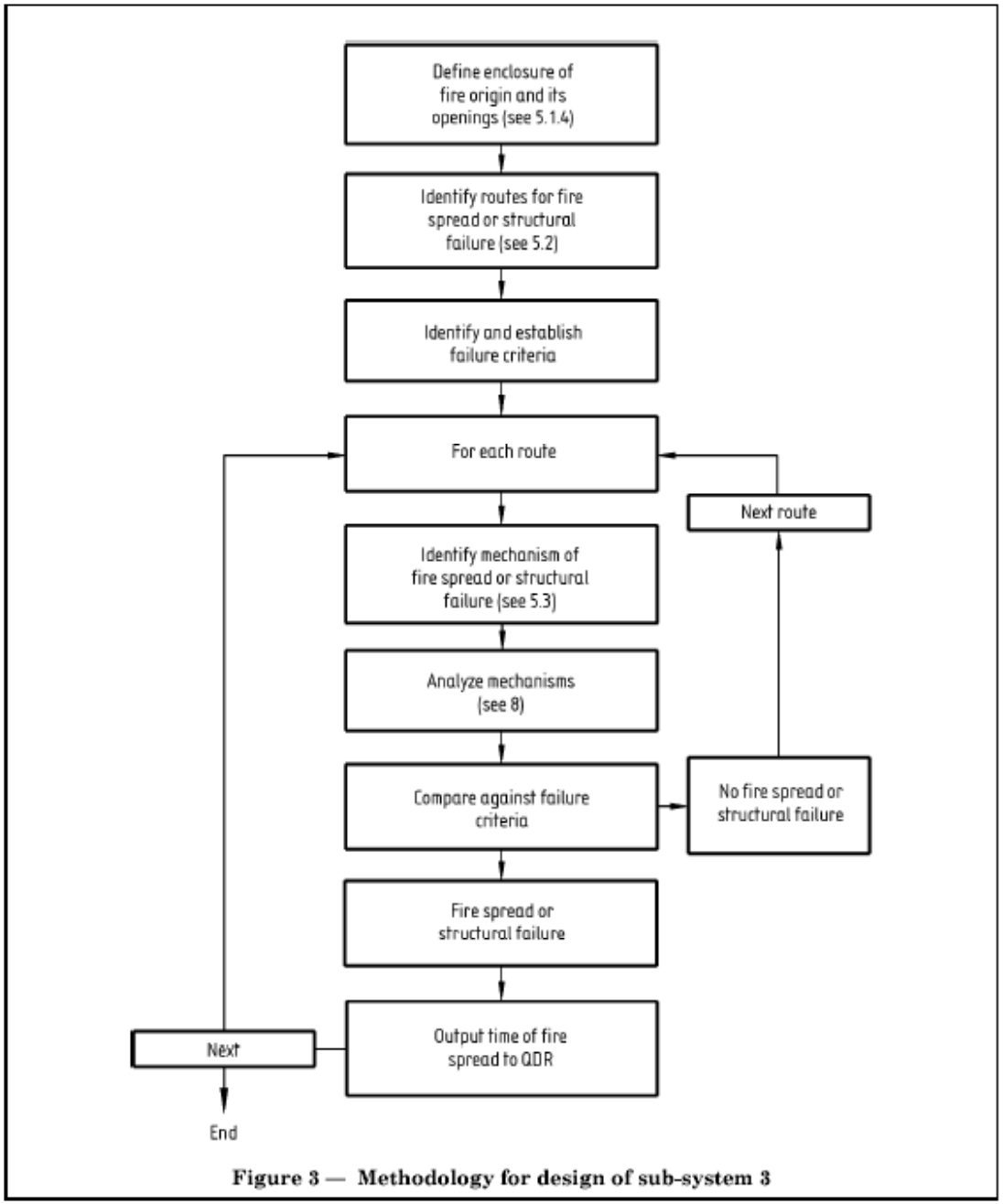
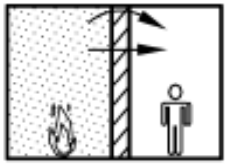
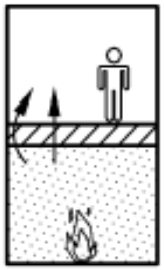
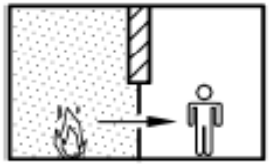
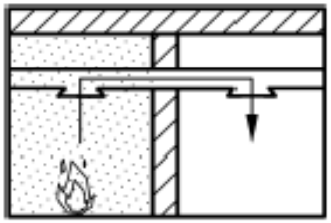


Figure 3 — Methodology for design of sub-system 3

SS3: Structural response and fire spread beyond the enclosure of origin (see PD 7974-3)

Example:

 Through wall or openings created in wall Spread mechanism: conduction, convection, direct pyrolysis (collapse)	 Through floor Spread mechanism: conduction, convection, direct pyrolysis (collapse)
 Through fixed opening Spread mechanism: convection, radiation, direct pyrolysis, mass transfer	 Along or through horizontal duct Spread mechanism: conduction, convection

Extracted from BS 7974

SS3: Structural response and fire spread beyond the enclosure of origin (see PD 7974-3)

Extracted from BS 7974

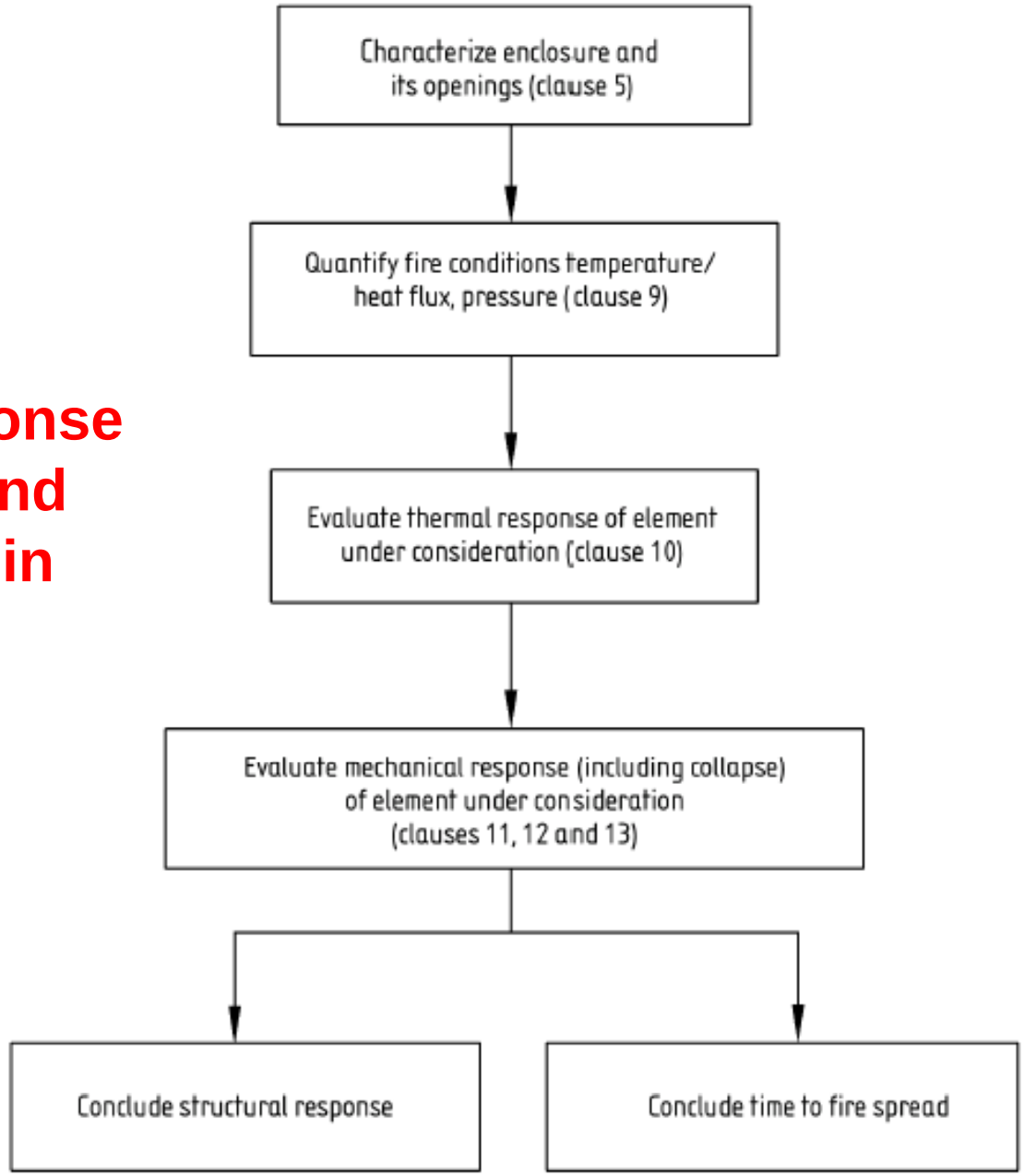


Figure 9 — Procedure for quantitative analysis of fire conditions

SS4: Detection of fire and activation of fire protection systems (see PD 7974-4)

- SS4 gives guidance on the calculation of the following with respect to time:
  - detection of the fire
  - activation of the alarm and fire protection systems, e.g. sprinklers, smoke venting systems, roller shutters, etc.
  - fire service notification.

SS4: Detection of fire and activation of fire protection systems (see PD 7974-4)

- Determination of objectives
- Required time to response
- Location and extent of detection
- Type of detection
- Siting and spacing
- Calculated time to response

SS4: Detection of fire and activation of fire protection systems (see PD 7974-4)

- Fire Control and Warning Systems
  - Determine the type and extent of local and remote fire warning systems and the likely response times of persons within the premises and fire fighting personnel.
  - Fire suppression systems
  - Fire barrier systems
  - Smoke control systems
- Review
  - A thorough review of each of the systems should now be undertaken to:
  - — ensure that the systems meet with the requirements of the fire safety engineering design;
  - — ensure that the systems function together as designed and that there are no adverse aspects created by the mutual interaction of any of the systems.

SS5: Fire service intervention (see PD 7974-5)

- SS5 provides guidance on the evaluation of the rate of build up of fire extinguishing resources of the fire service, including the activities of in-house or private fire brigades and in particular:
  - the time interval between the call to the fire service and the arrival of the fire service pre-determined attendance
  - the time interval between the arrival of the fire service and the initiation of attack on the fire by the fire service
  - the time intervals related to the build up of any necessary additional fire service resources
  - the extent of firefighting resources and extinguishing capability available at various times

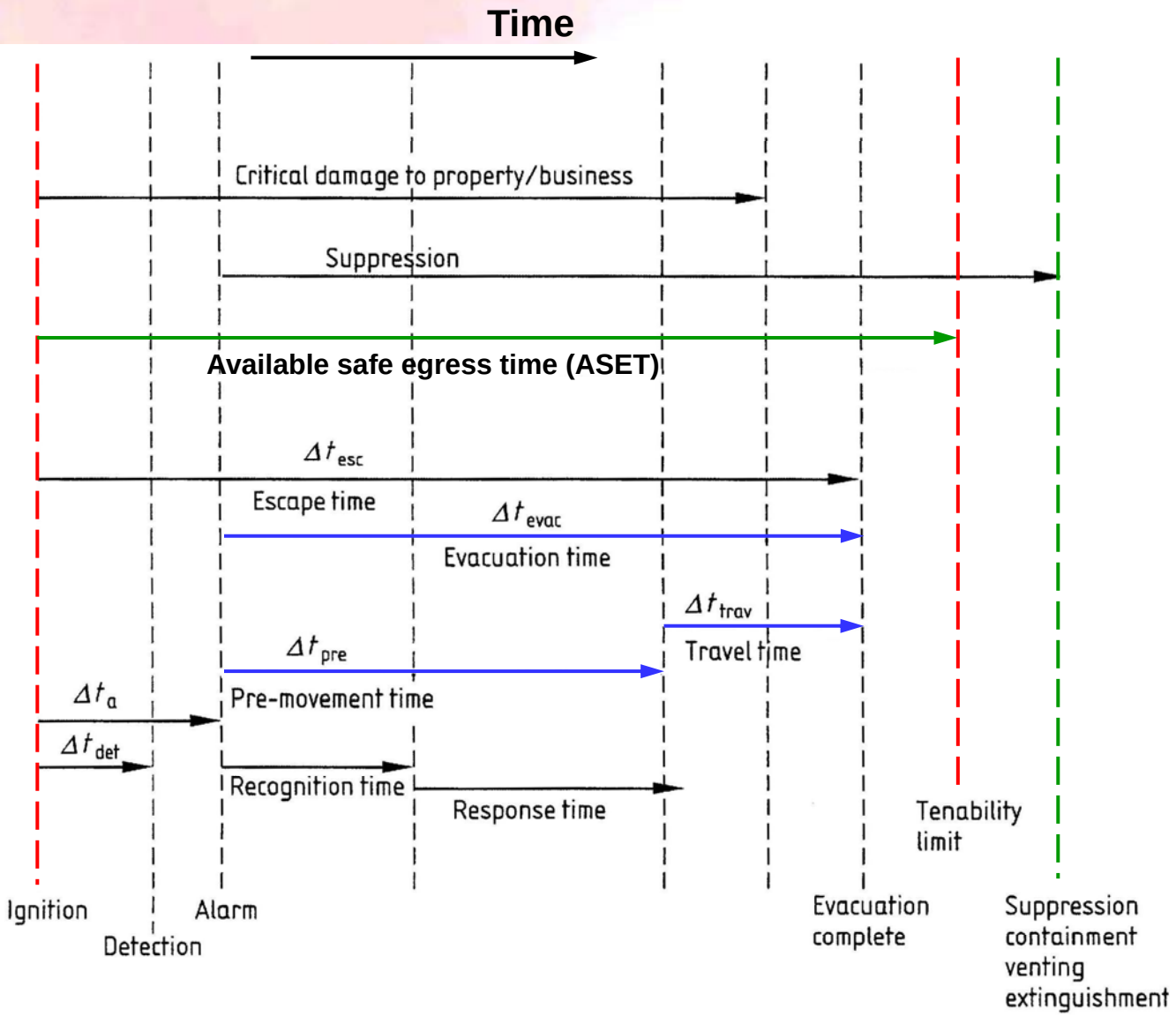
SS6: Evacuation (see PD 7974-6)

- SS6 provides guidance on how to assess the response of people to fire, including their evacuation time from any space inside a building.
  - Criteria for acceptance are contained in this sub-system.
- NOTE 1 The various parts of PD 7974 (PD 7974-1 to -6 respectively) for these sub-systems give selected data and engineering relationships (including information on their applicability) that may be used for design.
- This code of practice recognizes the use of alternative information

Time line approach

The time line approach

- ASET > RSET
  - ASET (available safe egress time) is the length of time available before untenable conditions are reached and might be defined in terms of:
    - a) the smoke layer height descending to within 2.0 m of floor level; and
    - b) the visibility distance falling below 10 m; or
    - c) the smoke layer temperature exceeding 200 C .
  - The untenable conditions vary among different standards
  - ASET can be estimated from using models



The time line comparison between fire development and evacuation/damage to property

Required Safe Escape Time

$$RSET = \Delta t_{det} + \Delta t_{alarm} + \left(\Delta t_{pre} + \Delta t_{trav}\right)$$

where

- Δt_{det} **is the time from ignition to detection which is determined from empirical model such Alpert's correlation,** Δt_{alarm} **is the time from detection to a general alarm**
- Δt_{pre} **is the pre-movement time for the building occupants and**
- **the** Δt_{trav} **is the travel time of the building occupants which is determined from the evacuation software such as SIMULEX, STEPS.**

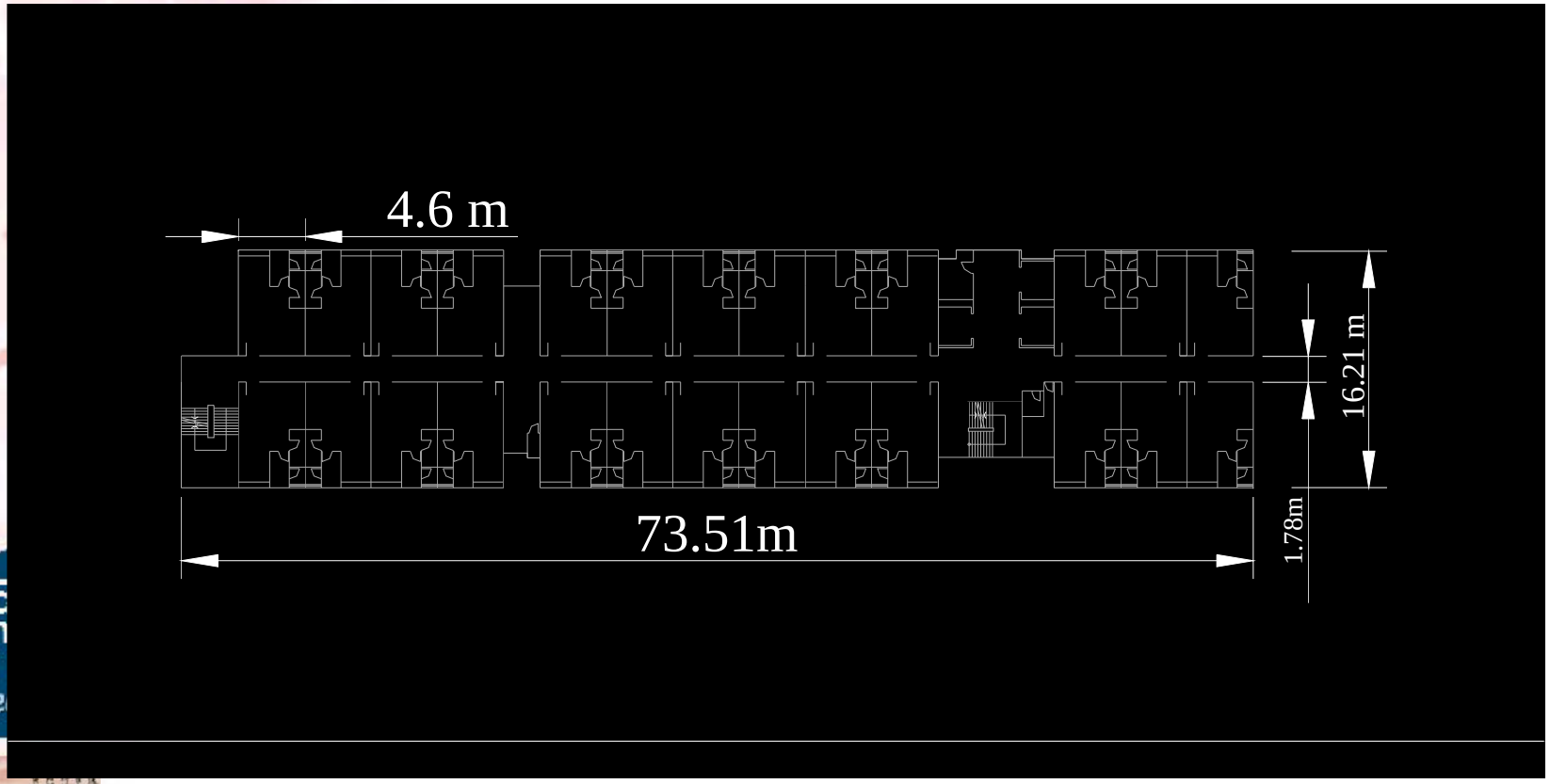
- **Based on above formula, it is apparent that a great delay in initiating evacuation (i.e. large value of Δt_{pre}) would lead to a considerable vulnerability of the occupants.**
- **Behavioral response of the occupants is one of the important factors affecting the evacuation time in the case of fire and would be dictated by their physical and psychological states at the time of fire awareness, e.g. whether they were asleep, just awake and not dressed, or dressed and awake, the severity of threat posed by fire, the building design and the fire protection devices installed.**
- **The reaction of occupants after the perception of fire would be affected by their perception of the seriousness of the fire.**
- **Before egress, many people tend to take preservative action, e.g. collecting important/valuable items.**

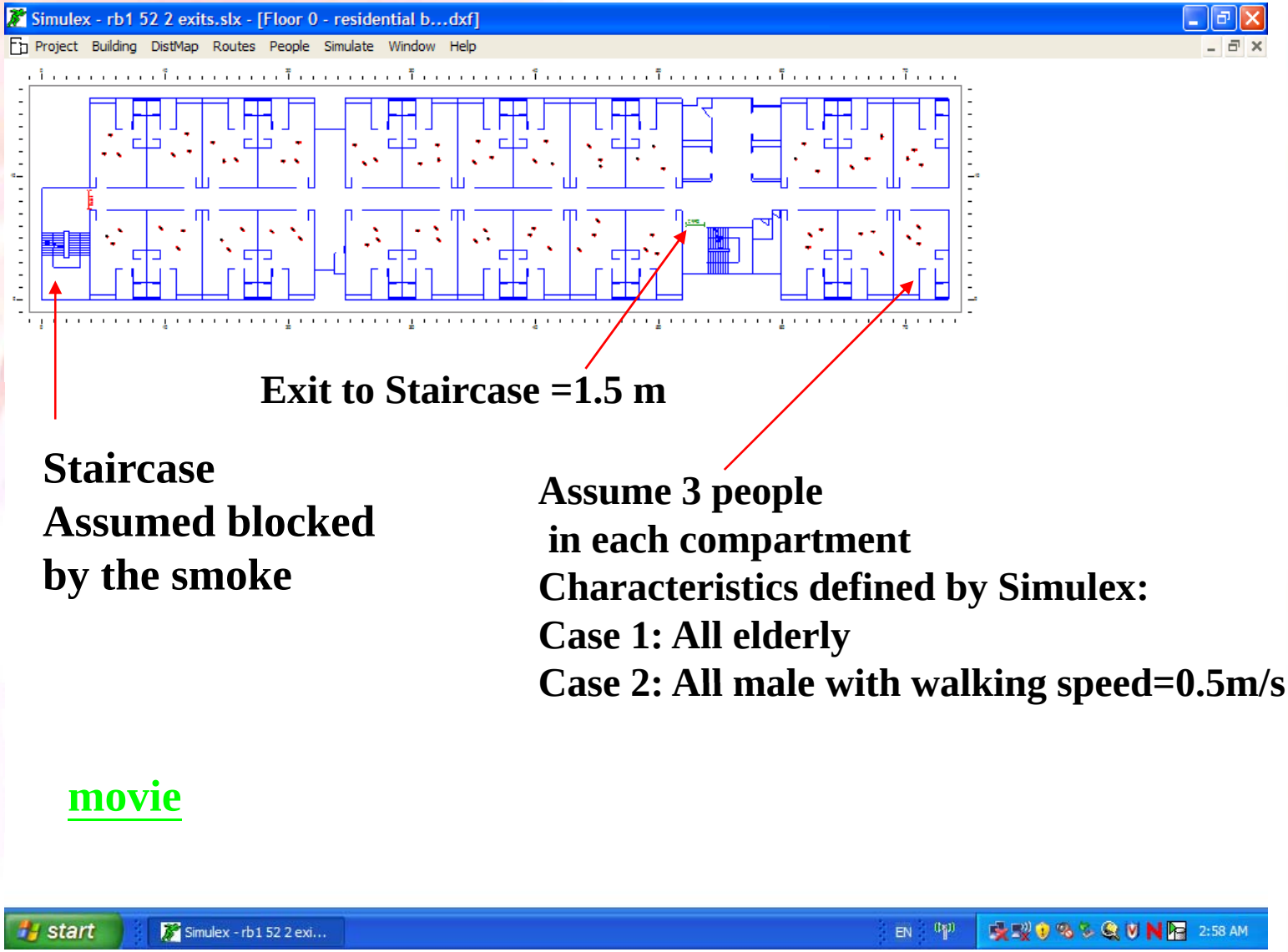
- **In estimating Δt_{pre}, the cognitive functioning ability of the occupants is very important. Some people would treat the audible fire alarm sound as a warning and wait for further information, e.g. notified by neighbor, clarified with management personnel via phone calls before starting to evacuate.**
- **Therefore, using this fire engineering approach for escape route design, it is important to understand the behavior of the occupants in the case of fire emergency such that Δt_{pre} can be determined and included in egress time calculations.**
- **However, the value of Δt_{pre} varied with considerable uncertainty and it is important to obtain accurate information of occupants.**
- **The determination of Δt_{pre} always leads to vigorous arguments between the designers/engineers and the authority.**

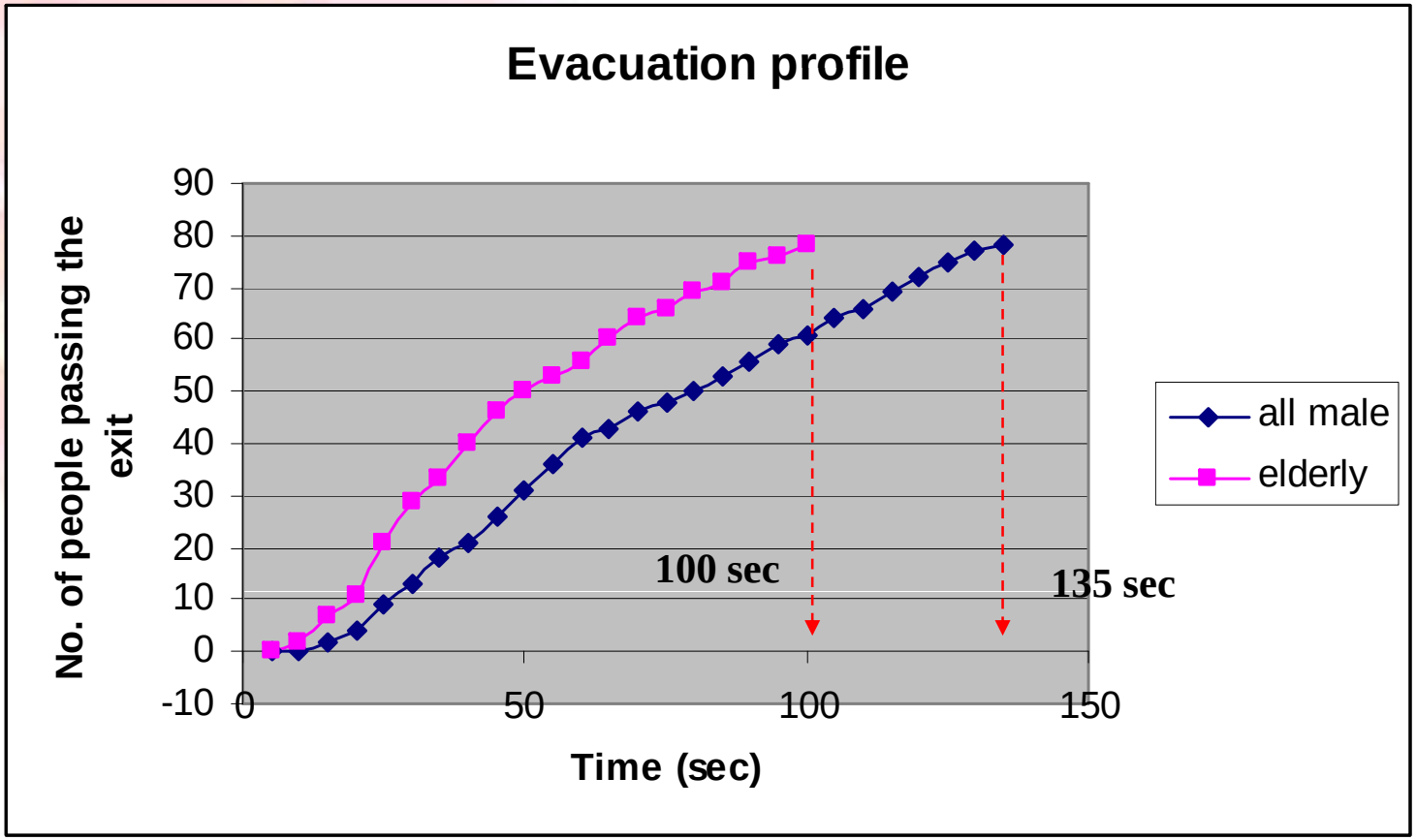
- **Physical conditions, occupant distribution, gender, age etc. are very important input parameters for the estimation of Δt_{trav} .**
- **However, in the existing fire engineering approach design, no universal guideline was developed in the determination of these input parameters.**
- **This again leads to arguments between the designers/engineers and the approving authority.**

Application Examples

Example




Simulex - rb1 52 2 exits.slx - [Floor 0 - residential b...dxf]
Project Building DistMap Routes People Simulate Window Help
Exit to Staircase =1.5 m
Staircase
Assumed blocked
by the smoke
Assume 3 people
in each compartment
Characteristics defined by Simulex:
Case 1: All elderly
Case 2: All male with walking speed=0.5m/s
movie
start
Simulex - rb1 52 2 exi...
EN
2:58 AM



The evacuation profile of two different occupant characteristics

- Only 1 typical floor with one 1.5 meter wide exit is considered in the simulation. Total number of occupants inside the floor is 78.
- The simulation setup is shown in figure. During the simulation, the response time of the occupants is based on random distribution with mean value equal to 1 min/s.
- Two occupant types are considered.
  - elderly type
  - all male with 0.5 m/s.
- For elderly type, the total evacuation time is ~100 sec.
- For all male with 0.5 m/s, the total evacuation time is 135 sec.
- This shows that by simply change the occupant type, the simulated evacuation time is increased by 35 %.
- A cumulative frequency curve is shown to illustrated the time required for the occupants to pass through the exit in floor 1.

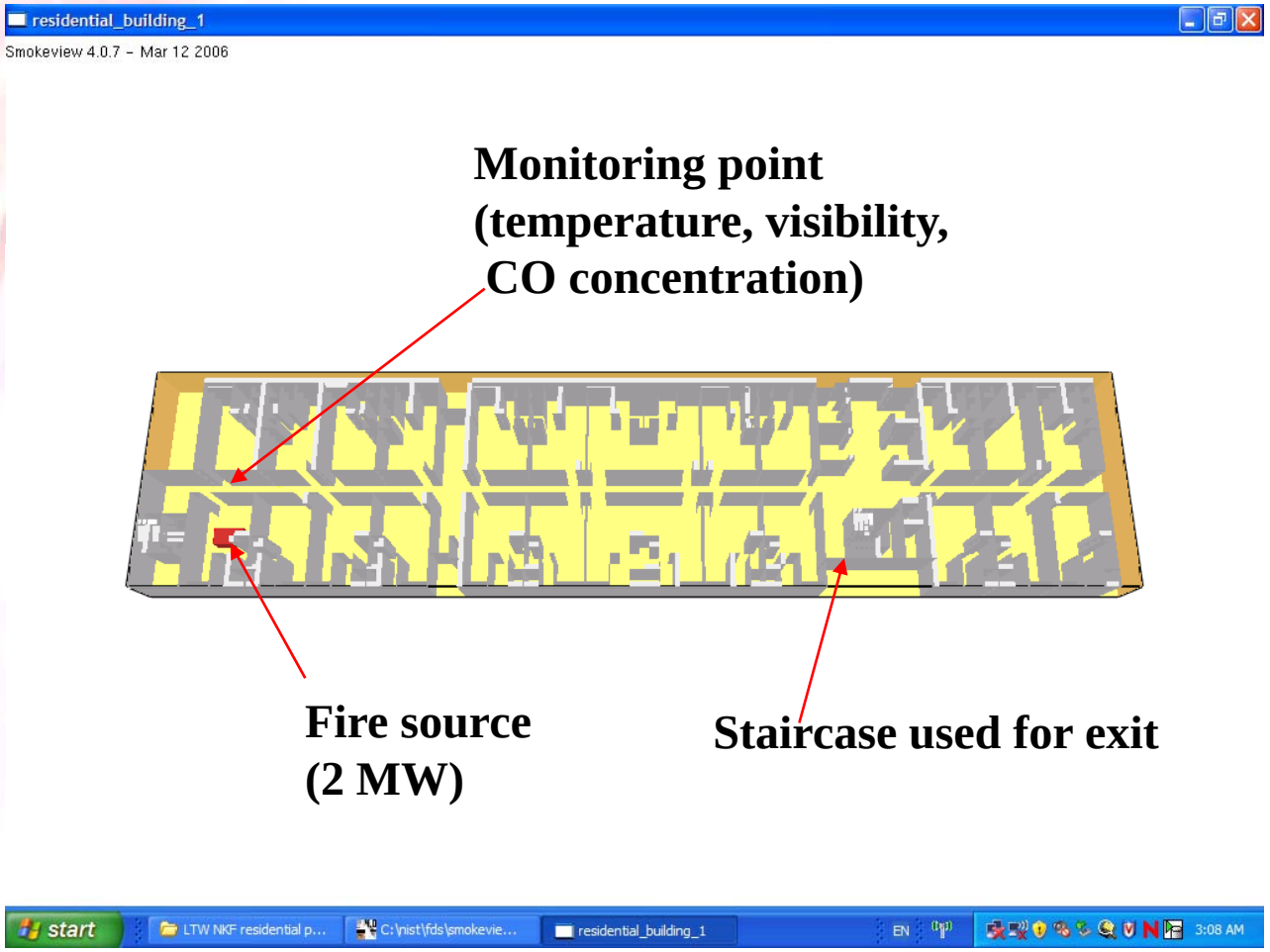
Untenable conditions

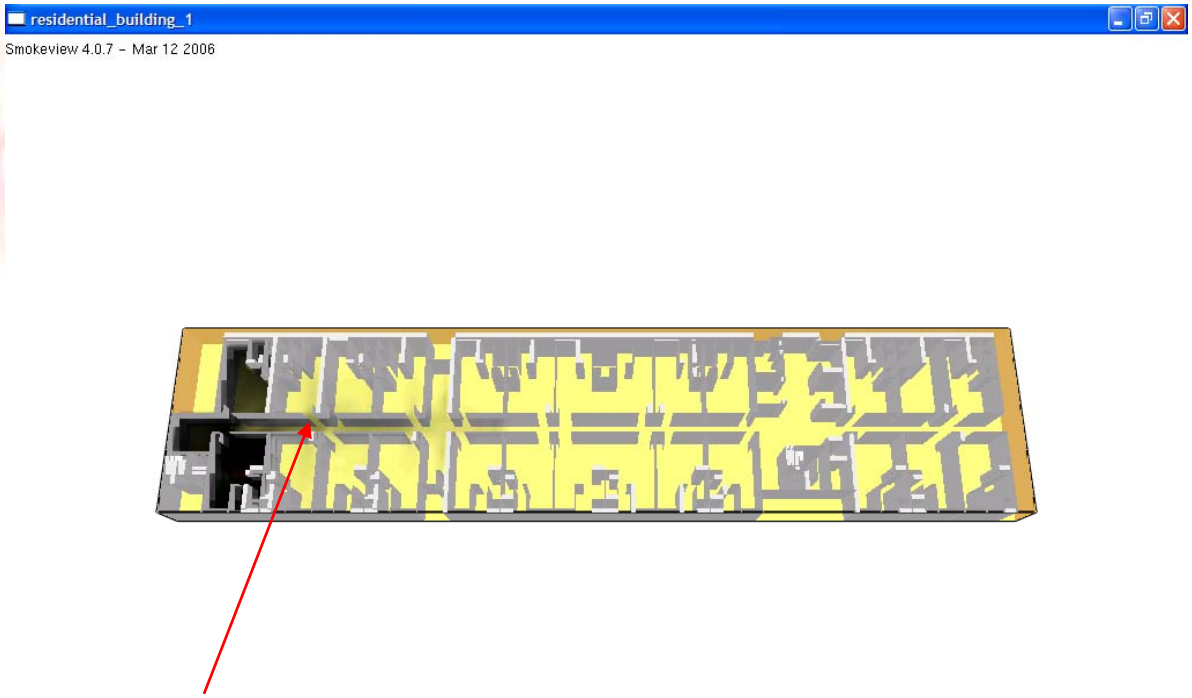
- The untenable conditions might be determined by the smoke layer clear height, thermal radiation from fire and enclosure temperature.
- The time from ignition to the occurrence of untenable conditions will be estimated and taken to be the available safe egress time (ASET) for the building occupants.
- For example, from PD7974-6:2004 of BS7974, the proposed tenability limits for smoke is $Dm^{-1}=0.08$ (visibility 10m).
- Other proposed tenability limits are 2.5kWm^{-2} for exposure to radiant heat, 115^{o}C for up to 5 minutes exposure to convected heat etc.

Estimation of the Fire Scenario

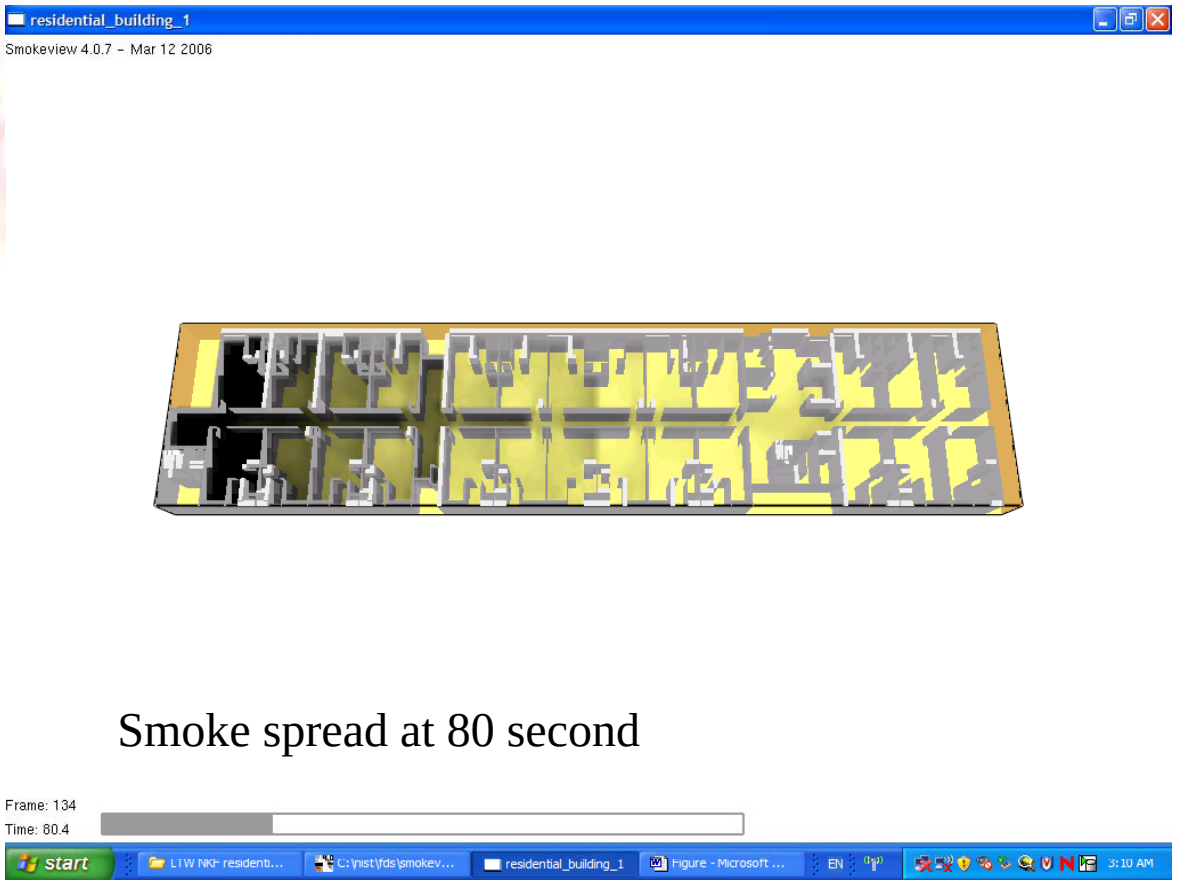
- For this example
- FDS is used to simulate the fire and smoke spread within this floor
- A typical floor layout is used for the simulation of the fire scenarios as shown in the figure.
- 200 x 40 x 6 (i.e. 48000) grid cells are used to perform the calculation.
- A fire size of 2 MW is used in one of the compartments for simulations.
- All the compartment walls are assumed 4 m high and assumed all doors are opened.

Simulation layout

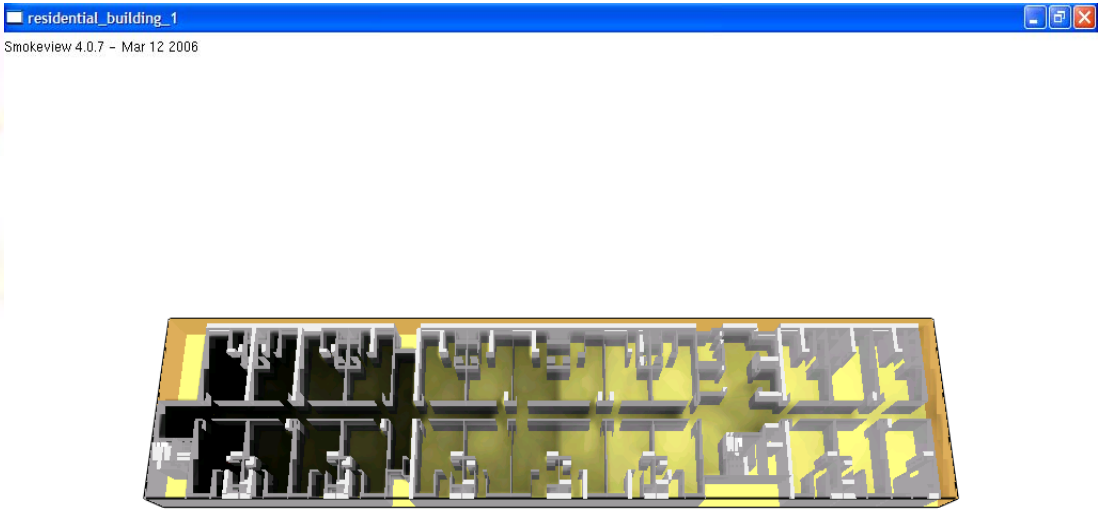




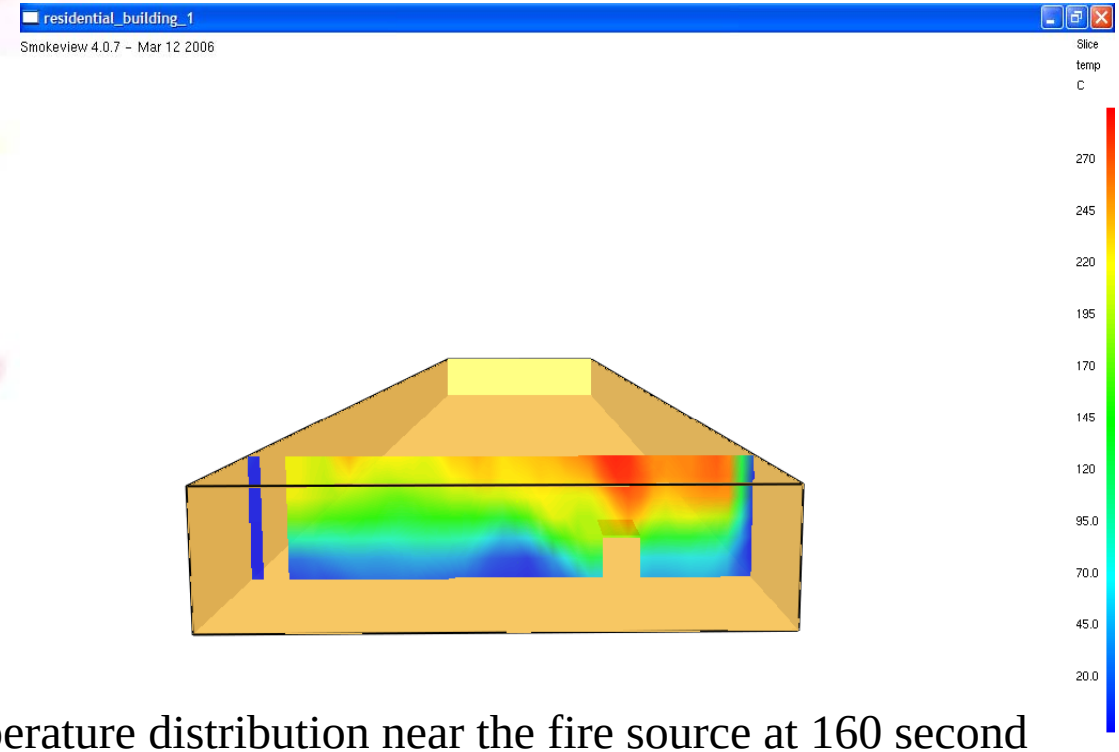
Smoke spread at 30 second



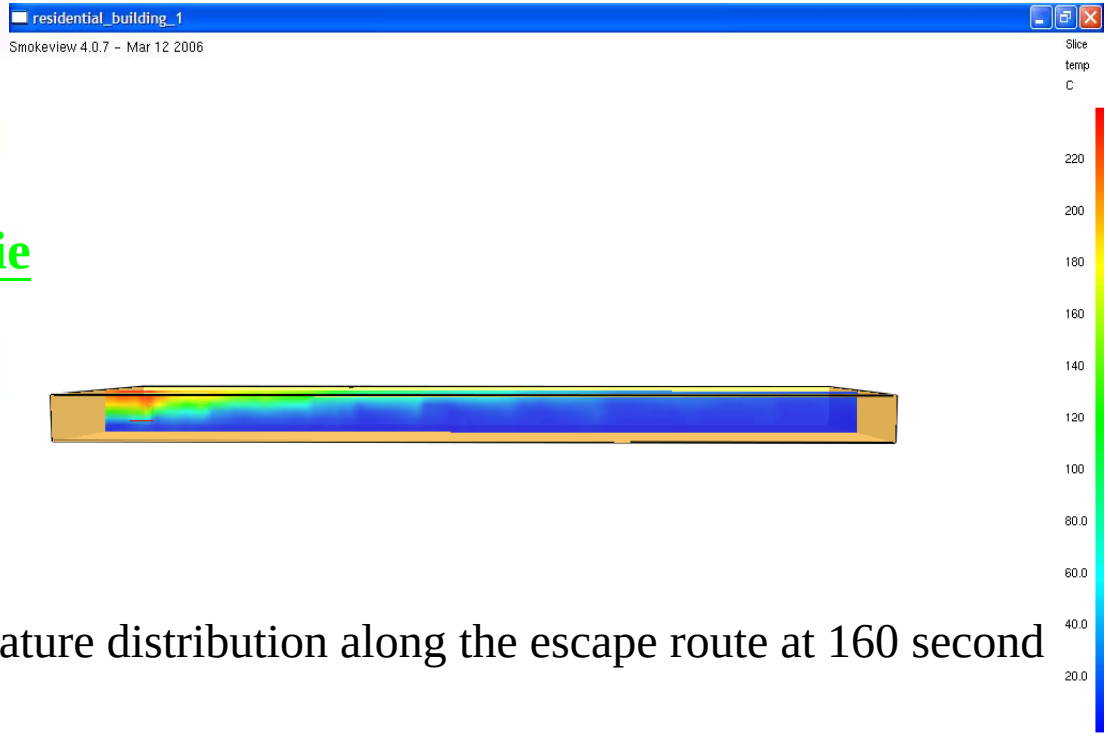
Smoke spread at 80 second



Smoke spread at 160 second

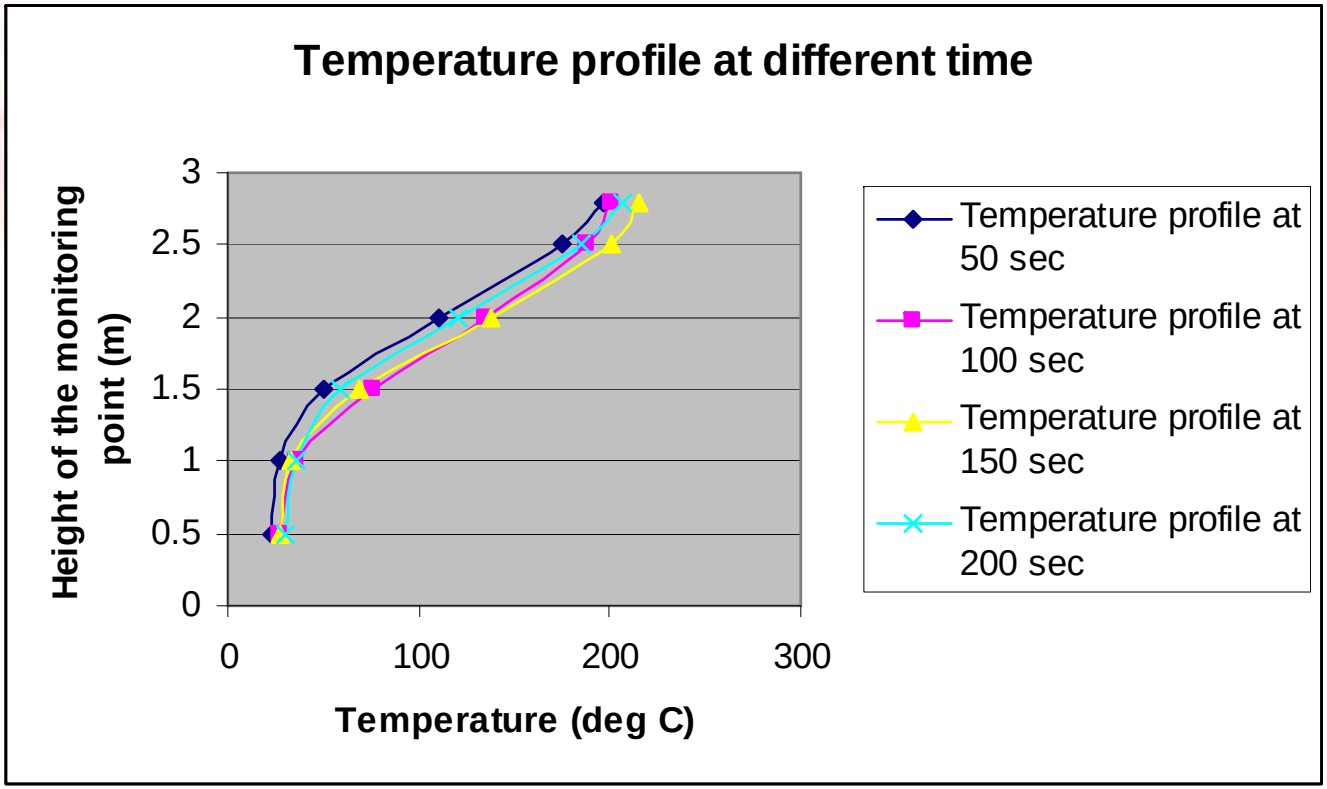


Temperature distribution near the fire source at 160 second



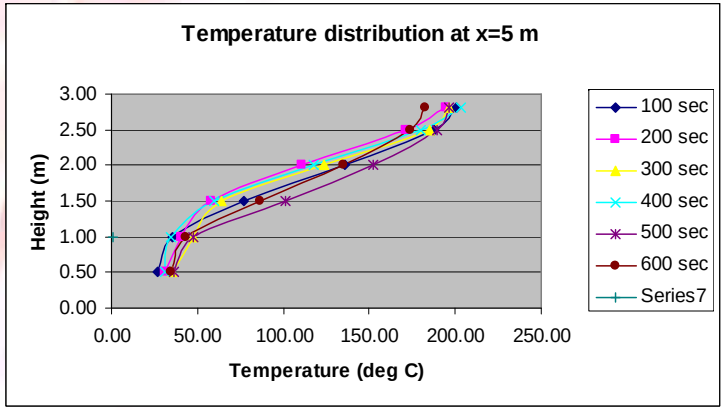
movie

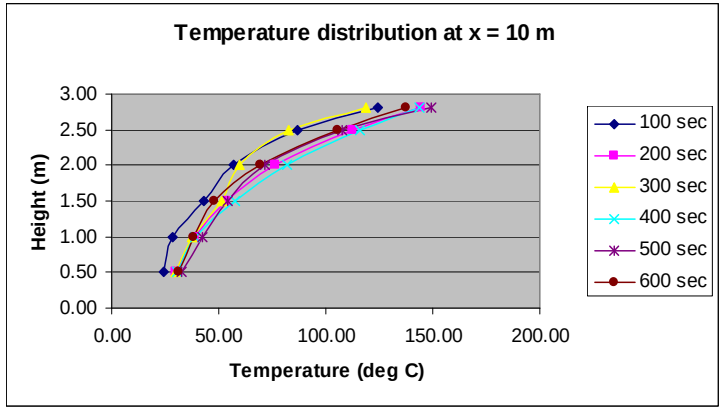
Temperature distribution along the escape route at 160 second

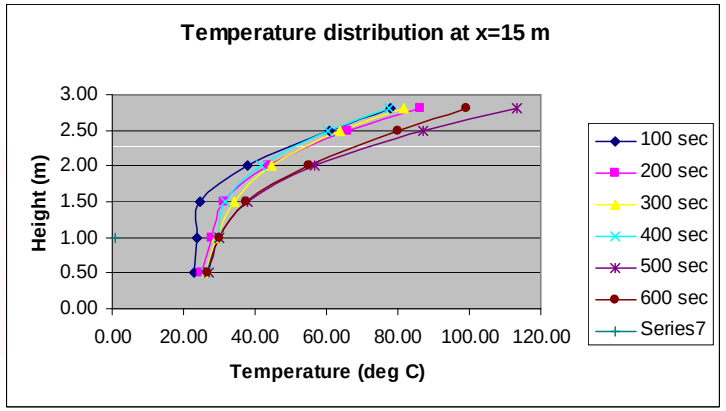


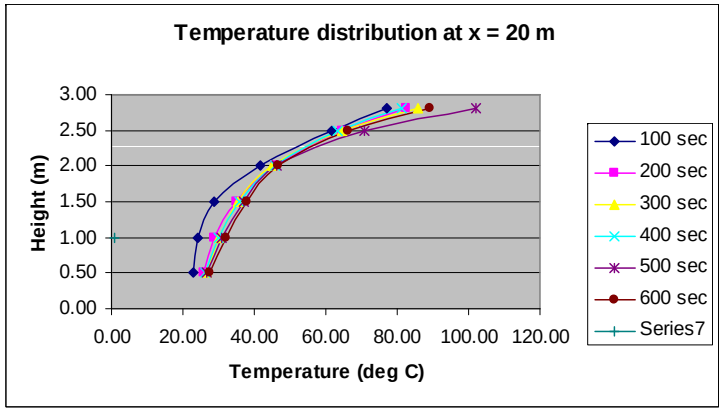
Temperature profile near the fire room at different time

Temperature Profile

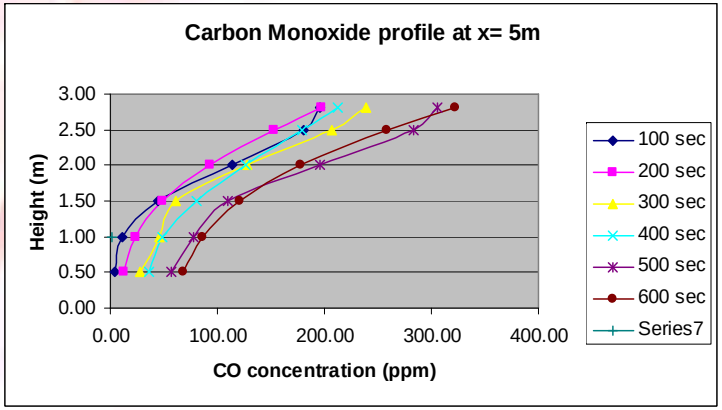


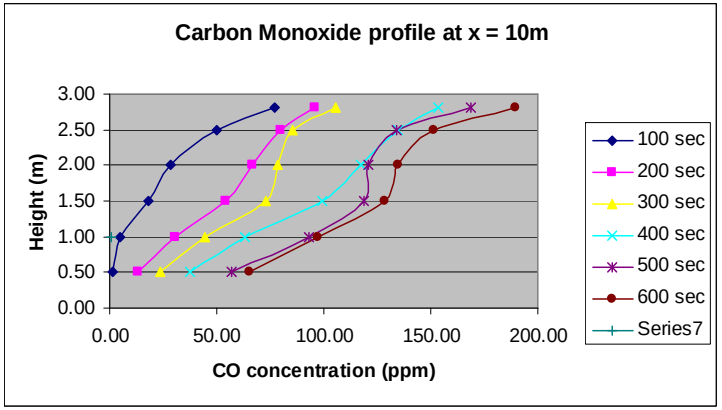


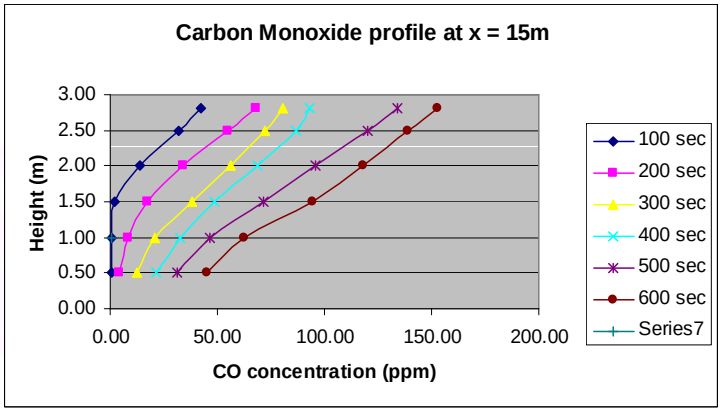


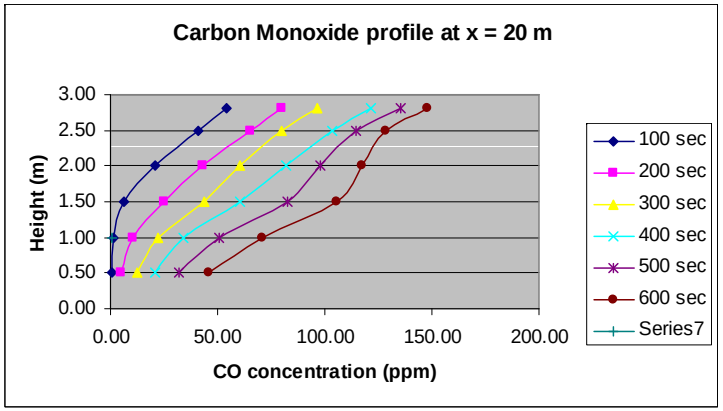


CO concentration profile

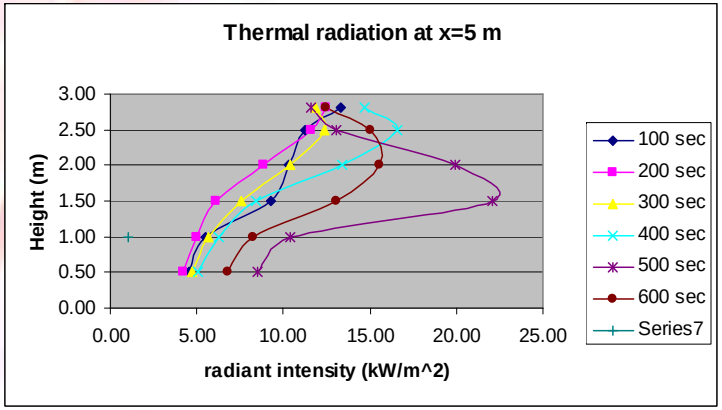


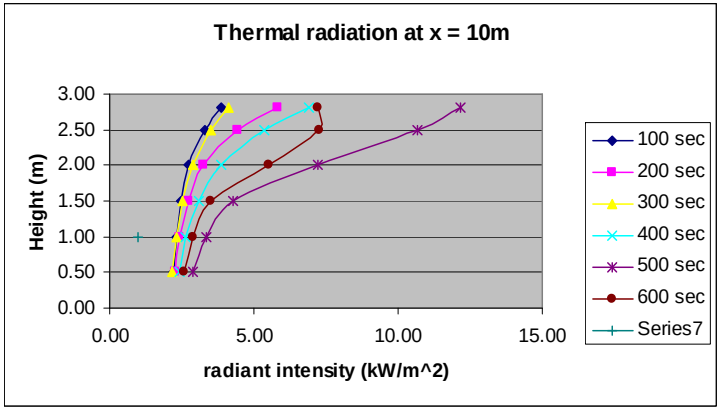


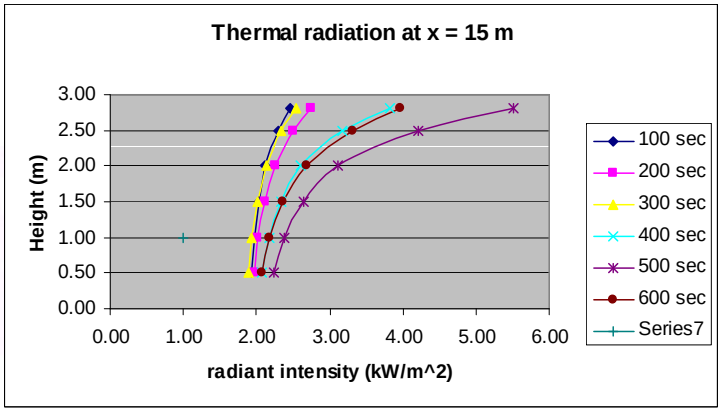


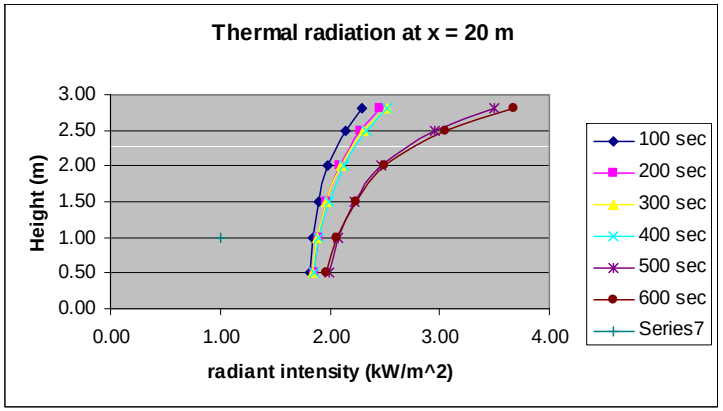


Thermal Radiation

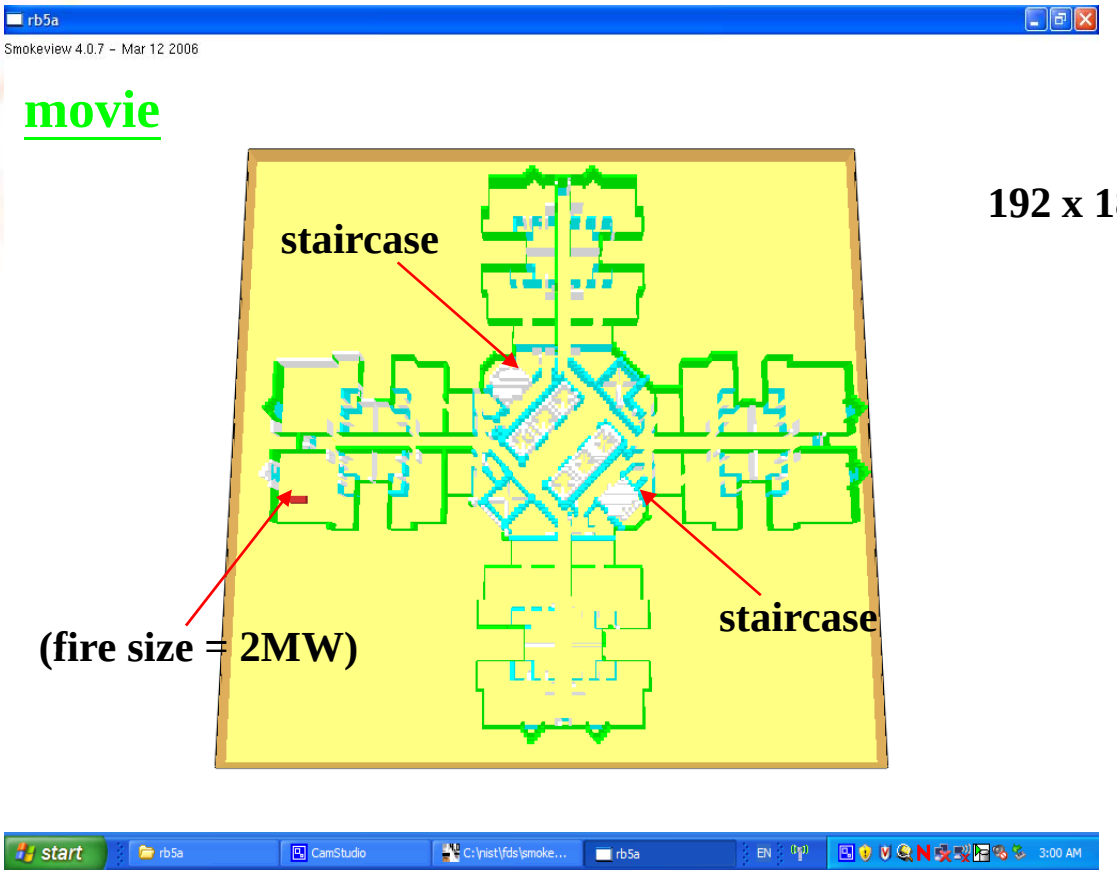




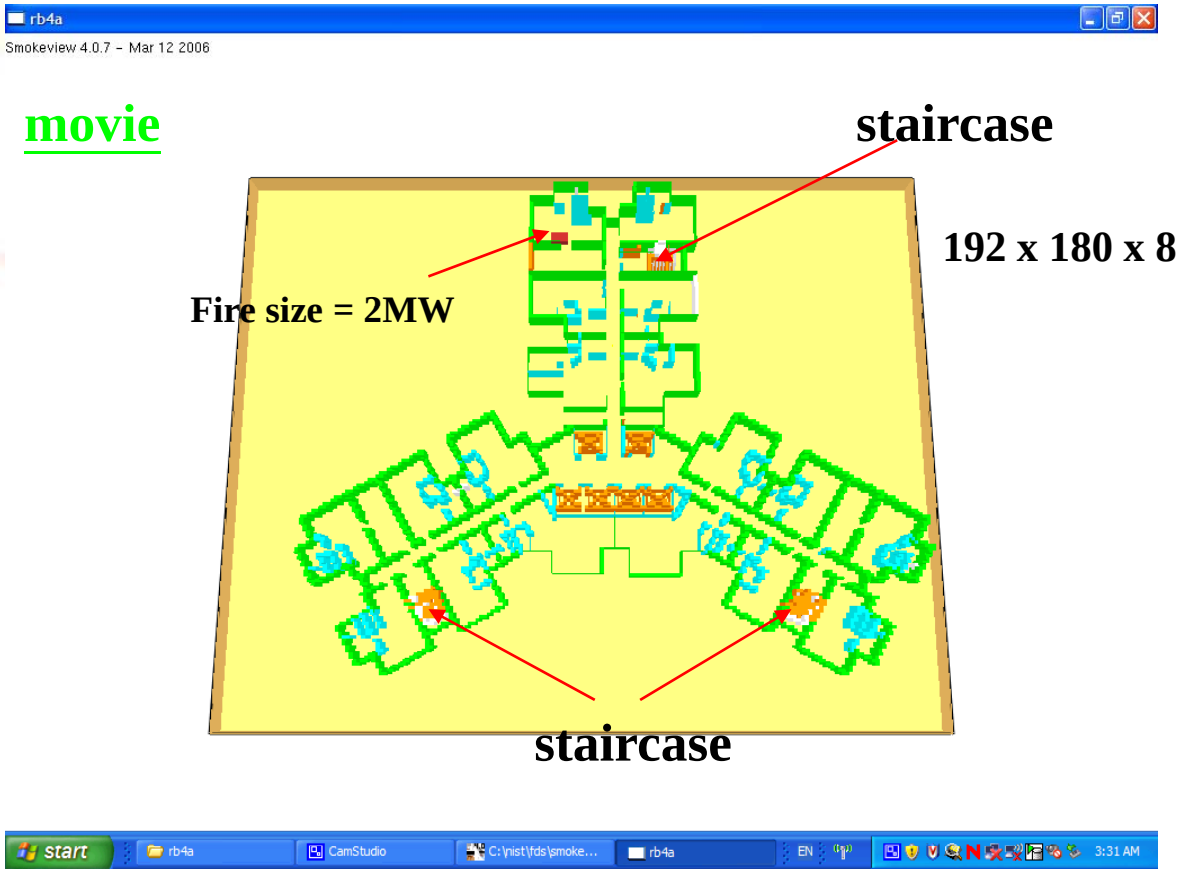




Other examples



192 x 180 x 6 grid cells


rb4a
Smokeview 4.0.7 - Mar 12 2006
movie
staircase
192 x 180 x 8 grid cells
Fire size = 2MW
staircase
start
rb4a
CamStudio
C:\nist\fds\smoke...
rb4a
EN
3:31 AM

Assessment and verification of model

- Verification
- Review of the theoretical basis of the model
- Comparison with other programmes
- Empirical verification
- Code checking
- Numerical accuracy
- Sensitivity analysis
  - E.g. Identify dominant variables in the model
  - Define acceptable range of values for each input variable
  - Demonstrate sensitivity of output variables to variations in input data

Conclusion

- Fire engineering approach / performance-based fire engineering design can help us to improve the fire safety design of the buildings.
- Care must taken to specify the input parameters, building characteristics, occupants characteristics, fire size, boundary conditions, models etc.
- For a good fire safety design, factors such as human behaviour, future modification, fire safety management etc, should also be considered.

Thank you !