Seminar Program

Fire Modelling :
A Design Tool for Performance-based Fire Codes

Friday, 16th March 2001	
Morning Session	
0830-0850	**Registration**
By 0850	**Guests to be Seated**
0855	**Arrival of Guest-of-Honour**
0900-0910	**Welcome Speech** *Mr. Chia Mia Chiang, Principal, Ngee Ann Polytechnic*
0910-0930	**Keynote Address** *Comr James Tan Chan Seng, Commissioner, Singapore Civil Defence Force*
0930-1000	**Tea Break**
1000-1045	**Paper 1 : Using Zone Models to Predict Fire Growth and Development - an Engineering Approach** *Cpt. Sakhubai, B. Sc., M. Sc. (SHE) and Cpt. Koh Thiam Hock, B. A. (Hons), SCDF*
1045-1130	**Paper 2 : BR 368e – Smoke Ventilation for Atrium Buildings** *Mr. Ho Nee Fun, B. Sc. (Hons), M. Sc. (Bldg Sc), C Eng., MCIBSE, MIES, Ngee Ann Polytechnic*
1130-1200	**Questions and Answers Session** *Session Chairman : Dr. Tan Chin Chong, B. Sc.(Hons), M. Sc. (Bldg Sc), Ph. D., Ngee Ann Polytechnic*
1200-1300	**Lunch**
Afternoon Session	
1300-1345	**Paper 3 : Development and Use of Fire Models – The Australian Experience** *Mr. Peter Johnson, B. Sc. (Physics), M. Sc. (FPE), FIE (A), MSFPE, Ove Arup & Partners*
1345-1430	**Paper 4 : Using a Fire CFD Program, JASMINE, as a Fire Engineering Tool** *Mr. Richard Chitty, B. Sc., MI Fire E (UK), Building Research Establishment, UK*
1430-1500	**Tea Break**
1500-1545	**Paper 5 : Field Modelling – Analysing the Airwell Design** *Cpt. Lim Lam Kwang, B. Eng., Joint FSB/FETC Project Team*
1545-1630	**Paper 6 : Development and Deployment of FiRECAM** *Dr. David Yung, B. Eng., M. App. Sc., Ph. D., National Research Council of Canada, Ottawa, Canada*
1630-1700	**Questions and Answers Session** *Session Chairman : Mr. Wong Kin Man, B. Sc.(Eng), M. Sc. (FSE), Ngee Ann Polytechnic*
End	

ORGANISING COMMITTEE

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Mr. Yuen Kum Tong

Paper 1

Using Zone Models to Predict Fire Growth and Development : An Engineering Approach

Cpt. Sakhubai, B.Sc., M. Sc. (SHE)

and

Cpt. Koh Thiam Hock, B. A. (Hons)

Joint SCDF/FETC Project Team

USING ZONE MODELS TO PREDICT FIRE GROWTH AND DEVELOPMENT : AN ENGINEERING APPROACH

Cpt Sakhubai and Cpt Koh Thiam Hock
Joint SCDF/FETC Project Team

BACKGROUND

The use of analytical models for predicting fire behaviour has evolved for decades. The combination of multiple phenomena and the creation of complex computer codes have allowed such models to be used in estimating the expected course of a fire based on given parameters. Today, fire models have progressed to the point of providing predictions of fire behaviour with an accuracy suitable for most engineering applications. This paper aims to provide an understanding of the underlying principles of zone models as a predictive tool in evaluating and calculating the evolving distribution of smoke and fire gases and temperature throughout a building / compartment during a fire. The paper will also show comparisons of data between that predicted by the model and the full-scale fire experiments conducted by SCDF and Ngee Ann Polytechnic.

With greater understanding and familiarity with the underlying physics of zone models, it is expected that its usages will definitely become more prevalent and successful over a wide range of applications. The capabilities of zone models must be recognised as a practical method for providing first order estimates of fire processes in enclosures and the benefits of utilising it as a tool, in particular, to achieve fire-safe building designs will be appreciated.

SCOPE OF PRESENTATION

The scope of this paper will be as follows:

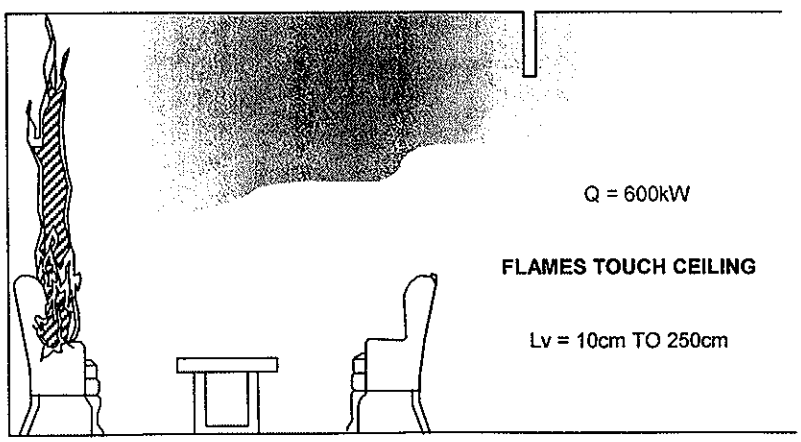
- Basic introduction of fire phenomena
- Zone Models and their Underlying Principles
- Brief overview of the most commonly and widely used accredited Zone Model, "FAST" (Fire Growth and Smoke Transport) Simulation model

- Comparisons of results between Live Fire Tests and predictions made by the "FAST" model
- Limitations, Applications and Advantages of Zone Models

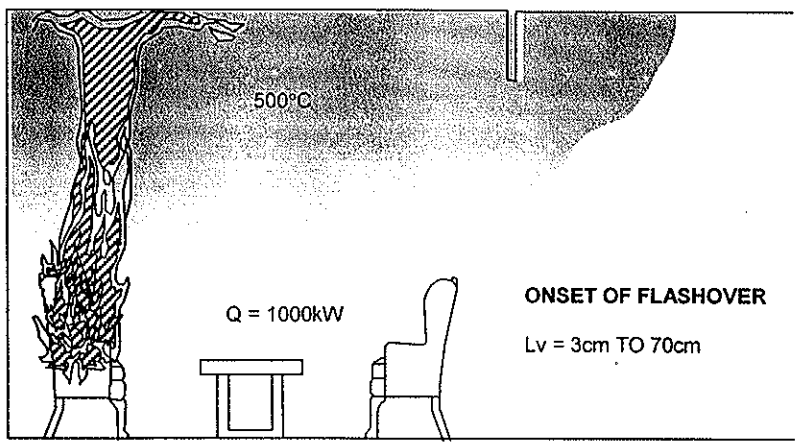
BASIC INTRODUCTION OF FIRE PHENOMENA

Fire Growth and Behaviour. Before attempting to understand zone models, it is necessary to have a basic knowledge of fire development and behaviour. Fire is essentially a chemical reaction in which a carbon based material (fuel) mixes with oxygen (usually as a component of air), heated to a point where flammable vapors are produced. Basically, anything that contains wood, plastic, paper, fabric, or combustible liquids should be considered a fuel. The flammable vapors will spread until they either dissipate or come in contact with a sufficiently hot item (an ignition source). If sufficient disbursement happens, the fire risk is eliminated. If the latter occurs, however, a combustion process begins.

Many fires within enclosures, if allowed to grow unchecked, is known to progress through four predictable stages of development. Each stage has a characteristic feature and the effects vary according to the fuel load. The duration of each stage will vary with the circumstances of ignition, fuel load and the availability of ventilation but the sequence of the fire development will never defer i.e. incipient fire, flashover, free burning and fire decay. The stages of fire growth can thus be classified as follows:



→ **Developing Stage.** This is the first stage of fire development after ignition. A typical fire begins as a slow smouldering process, which may last from a few minutes to several hours. This smouldering duration is dependent on fuel type, arrangement, and availability of oxygen. A fire that increases its instantaneous energy output or heat release rate over time is said to be a growing or developing fire. Typically, developing fires have more air available than is needed for combustion of the fuel gases being generated and will continue to grow until limited either by the amount of fuel available (fuel controlled fire) or the amount of air for combustion (ventilation controlled fire). Heat generation increases and the smell of smoke is usually the first indication that a fire is underway. Heat permits the onset of open, visible flames. The appearance of flames indicates that a fire has changed from a relatively minor situation to a serious event. The flame development is localised and free burning open flames are typical. There is a plume of hot gases rising from the flame. The contents of this plume will depend on the fuels being burnt but usually include soot, water vapour, sulphur dioxide, carbon dioxide, carbon monoxide and traces of other toxic gases. Convection carries these products and heat to the upper parts of the rooms and draws oxygen in at the bottom of the flames to sustain combustion.



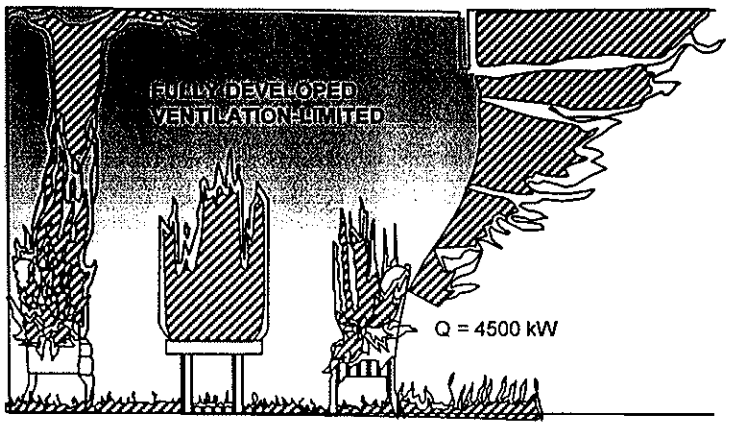
→ **Flashover Stage.** The fire spreads laterally along ceilings. Convection, conduction and direct flame impingement spread the flames up and out from the initial fuel until nearby material reach their ignition temperature and begin to burn. The radiant heat from the flames begins to bring other fuels to their ignition temperatures spreading the fire laterally. The speed of this lateral spread is dependent on how close the other fuels are and their physical arrangement.

As more fuel is being burned, the fire grows in intensity. Hot gases, if confined, will mushroom filling the entire room. The mushrooming hot gases, heated ceiling and upper wall surfaces radiate energy down to the unignited materials below in the room. The closer the ceiling is to the burning materials, the more heat it will radiate. Ceiling and wall finishes that are combustible will have a significant influence on the fire growth and fire spread. The other contents in the room ignite and temperatures may be sufficiently high to `flash'.

The hot gases generated from the fire gather at the ceiling in a dense cloud layer. This upper layer of the room with its low oxygen content, high temperature, soot, smoke, and partially burned pyrolysis products (including toxic gases such as carbon monoxide, hydrogen cyanide, hydrogen chloride, acrolein, and incompletely reacted chemical species called free radicals) is not very different from that near the floor. The floor layer is still relatively cool and contains fresh air (with an oxygen concentration close to normal) that is being mixed with the flames and clouds of reaction products. Survival is still possible in the room if one stays in the cooler lower layer and does not breathe the gases higher up. If ventilation to the room is limited, the flames will produce more incompletely burned material, which can be seen as soot and smoke. The levels of these fuel rich mixture grows lower and lower in the room, its temperature increasing as the fire continues and the flames grow. The mass of combustible gases, aerosols, soot, and smoke accumulate until one or more of the fuel presents reaches its ignition temperature.

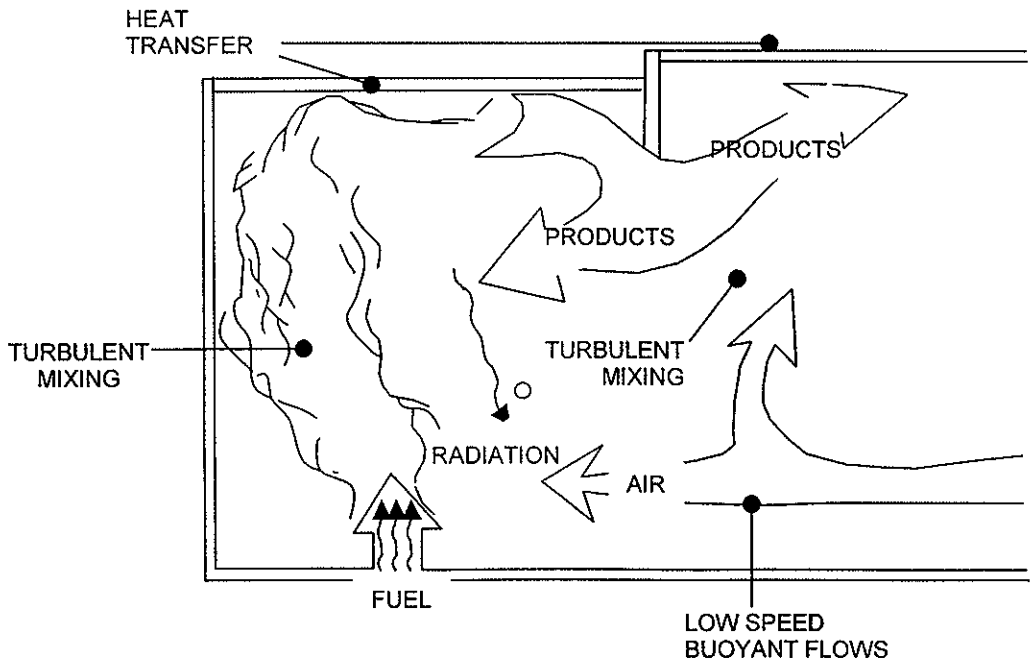
The clouds of airborne fuel then catch fire and the flames may extend throughout the room at ceiling level. The flame front in the rolling cloud of fuel and air can reach speeds of about 3-5 meters/second. With combustion proceeding in that layer, the temperature of the ceiling layer increases even faster. When this layer reaches a critical temperature of approximately 600 degrees Celsius, it is generating sufficient radiant energy to bring other fuels in the room to their ignition temperatures.

At this time, all fuels in the room burst into flaming combustion simultaneously, and the room is said to have undergone flashover. Flashover is usually defined as the sudden and dramatic simultaneous ignition of most combustibles and gases in a room, resulting in a fully involved compartment fire.



Free Burning Stage. Once flashover occurs, temperatures throughout the room are at their maxima and survival for more than a few seconds is impossible. This stage is marked by flames fully encompassing the room, with the likelihood of flames emerging from windows and doors. Once all the contents in the room are burning, the heat release rate goes into a steady burning phase. Under steady-state conditions, the fire's heat output or heat release rate remains relatively constant over time. There would be no rapid increase or continuing decrease in energy release rate due to the fire burning at a constant heat release rate.

Decay Stage. This is the stage where the fire is under decay conditions, that is, there is plenty of air for combustion but the heat release rate is decreasing due to fuel consumption. The fuel is exhausted and the decline is often specified as the inverse of the growth or developing curve. This means that fast growth fuels decay fast and slow growth fuels decay slowly.



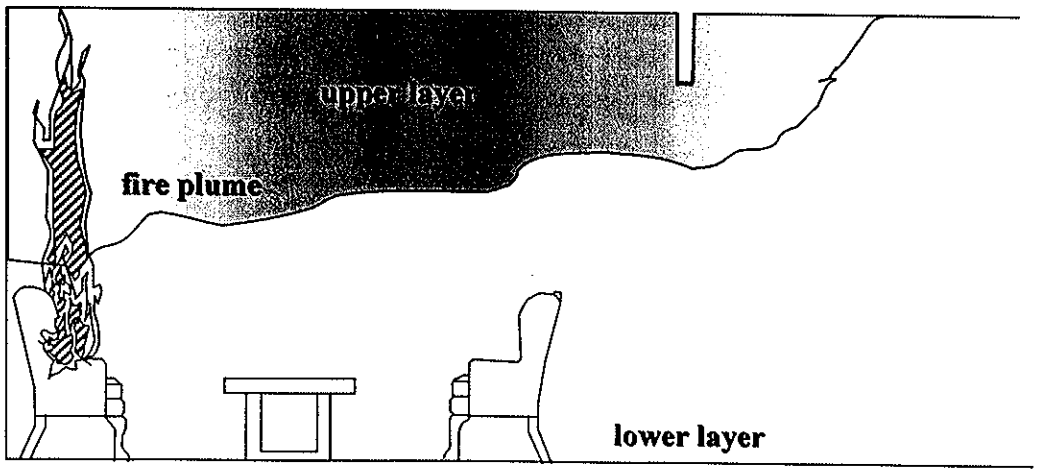
FIRE MODELING

It is the recognition of the fire phenomena arising in a room as summarised in the diagram above that help establish a framework for the modelling of compartment fires. As fire grows and develops in a rather predictable manner, it is possible to mathematically predict and model a fire situation and its effects.

Fire models can be classified into two broad categories, namely physical model and mathematical model. Physical models are a copy of real fire situations on a reduced scale. All standard fire tests are physical models of fire behaviour. However, the method of physical fire modelling is expensive and cumbersome. The second type of fire models are mathematical models. Mathematical models are a set of equations that describe the behaviour of a physical system. This is also termed "Deterministic fire model" and they were developed based on a mathematical representation of the underlying physics of fires. The mathematical equations are re-cast into predictive equations for temperature, smoke and gas concentration, and other parameters of interest, and are coded into computer for solution. A mathematical deterministic computer model can thus compute the conditions produced by the fire at a given time in a specified volume of air. It assumes that the predicted conditions within this volume are uniform at any time. Deterministic fire models can be further sub-divided into 2 separate groups, namely "zone" models and "field" models. For the purpose of this paper, only `zone' models will be analysed and discussed.

ZONE MODELS AND THEIR UNDERLYING PRINCIPLES AND PHYSICS

The basis for zone models was first published by Fowkes (1973) in his description of `bedroom fires' series conducted by Factory Mutual Corporation. Other researchers around the same time also produced zone model computer programs. Since then, a large number of computer programs have been developed. The fire phenomena are characterised by small numbers of zones (usually 2 or 3), which are of uniform temperature and yields of product species. The zones may include the fire or combustion zone, the plume, the compartment hot gas zone or upper layer, the compartment ambient zone or lower layer, and the outside ambient zone. Usually, 2 zones are utilised, the hot upper layer and the cooler lower layer.



The following are some underlying principles and physics of zone models.

- Zone models utilise the concept of control volumes or zones within which the conditions (e.g. temperature, pressure, density etc) are assumed constant. The concept evolved from observations of 'layering' in real fire experiments. Most models assume that the compartment to be consisting of two regions: (1) an upper layer, filled with hot combustion gases, and (2) a lower layer, filled with essentially cool air. Each layer or zone is thus visualised to have uniform temperatures and gas concentrations. The plane that divides the zones is the hot layer interface that may move vertically during a fire.
- The basic building block of zone model is the mass, energy and momentum conservation equations for the zones. These are the fundamental laws of physics.
- In areas where knowledge gaps exist to explain the phenomena, empirical correlations based on experimental observations are adopted (e.g. entrainment coefficients).
- It is assumed that air follows the ideal-gas law and that a time-squared equation is often used for the initial growth stage.
- It is assumed that pressure is uniform within the compartment, that is, $P_{upper} = P_{lower} = P$. Work done by the air volume is relatively small and often ignored in most zone modelling programs. The FAST program accounts for this.
- A flat maximum and a decay stage are often included in the analysis.

- In zone models, it is also estimated that 60 to 90% of the heat released could be transferred to the bounding surfaces (walls, ceilings and floors) through conduction, convection and radiation.
- The fire plume acts as a pump for the mass to flow from the lower zone to the upper zone through the process of air entrainment. It is assumed that heat released from the source comprises two portions, the radiative and convective portions.
- The depth and temperature of an upper layer can be calculated by considering the mass and energy within the layer.
- Vent flows are governed by pressure differences across the vent and Bernoulli's equation is used to solve momentum conservation. In zone models, vent flows can take several forms, including horizontal, vertical and forced air flows.
- Mass concentration of species can be calculated by considering conservation of existing species in the zones and the mass production rate of species due to combustion.

OVERVIEW OF FAST (FIRE GROWTH AND SMOKE TRANSPORT)

FAST is a computerised zone modeling software developed by National Institute of Standards and Technology (NIST) that predicts the effect of a specified fire on temperatures, various gas concentrations and smoke layer heights in a multi-compartment structure. It is widely used by many as it is moderately easy to use and can be downloaded from the internet for free. It can simulate fires and monitor the fire and smoke transport up to 30 enclosures. Within FAST, a fire is a source of fuel, which is released at a specific rate. This fuel is converted into enthalpy and mass as it burns. Burning can take place in the portion of the plume in the lower layer, upper layer, or in a door jet. It has the ability to track, independently, multiple fires in one or more rooms of the building. All burning objects give off a plume, which acts as pump for enthalpy and mass from the lower layer into the upper layer. FAST uses empirical correlation to determine the mass flow between the layers and it is able to factor other source of mixing at vents such as windows and doors which can connect both to enclosures or to the outside and can be programmed to be open or closed versus time. The flow at vents

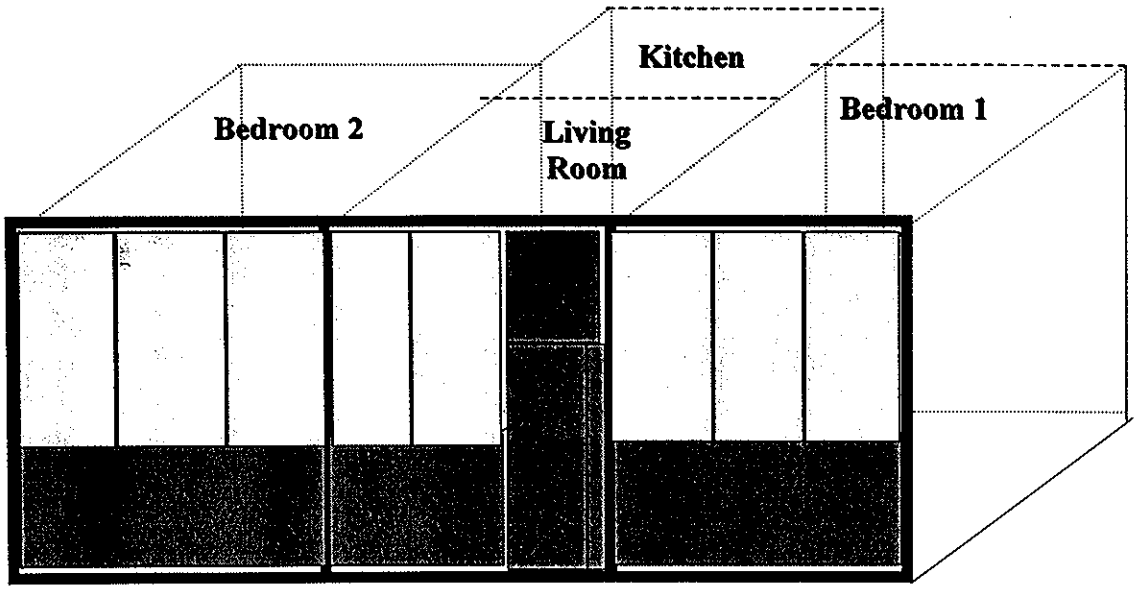
is modelled as a plume [jet]. In addition, it can simulate heat transfer through the wall ceiling, or floor in conjunction with differing material properties. Other features are also available to identify the effectiveness of smoke ventilation systems and to account for sprinkler and detector activation in determining available egress times. Within FAST, there is also a database of common properties of materials and the user can choose the thermal properties of bounding surfaces. The outputs expected from FAST can include temperature of upper and lower layer, smoke layer height, optical density, species concentration and heat release rate, among others.

CONDUCT OF LIVE COMPARTMENT FIRE TESTS

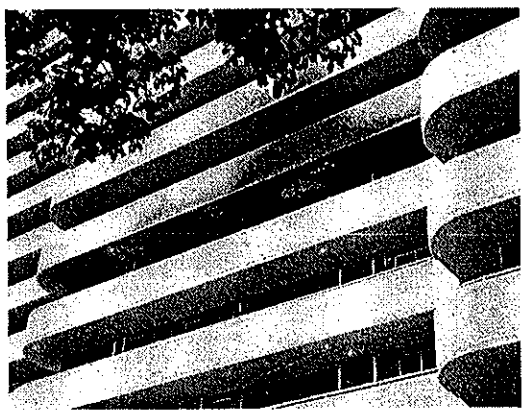
To validate the "FAST" zone model, a series of live fire tests were carried out. The actual data captured in these fire tests, i.e. temperatures, species concentration etc, was then compared with the predictions made by "FAST". Live compartment fire tests were successfully simulated in fully-furnished three-room residential units on the 6th Oct 2000 (Block 39 Forfar Square) and 22th Feb 2001 (Block 110 Depot Road) respectively at the two different locations to evaluate the predictive abilities of the FAST model. The tests were conducted to obtain data to:

- Examine the temperature build up in the room of fire origin and the interconnecting rooms;
- Examine the time to flashover;
- Examine the smoke layer height in the adjoining rooms;
- Examine the Carbon Monoxide (CO) species concentration produced in the room of fire origin.

The first test (**Fire Test 1**) was carried out at (#06-126) at Blk 39 Forfar Square which is a three-room HDB residential unit having the following physical arrangement. Photographs of the burn room before the test are also appended below.



Layout of Residential Unit at Forfar Square



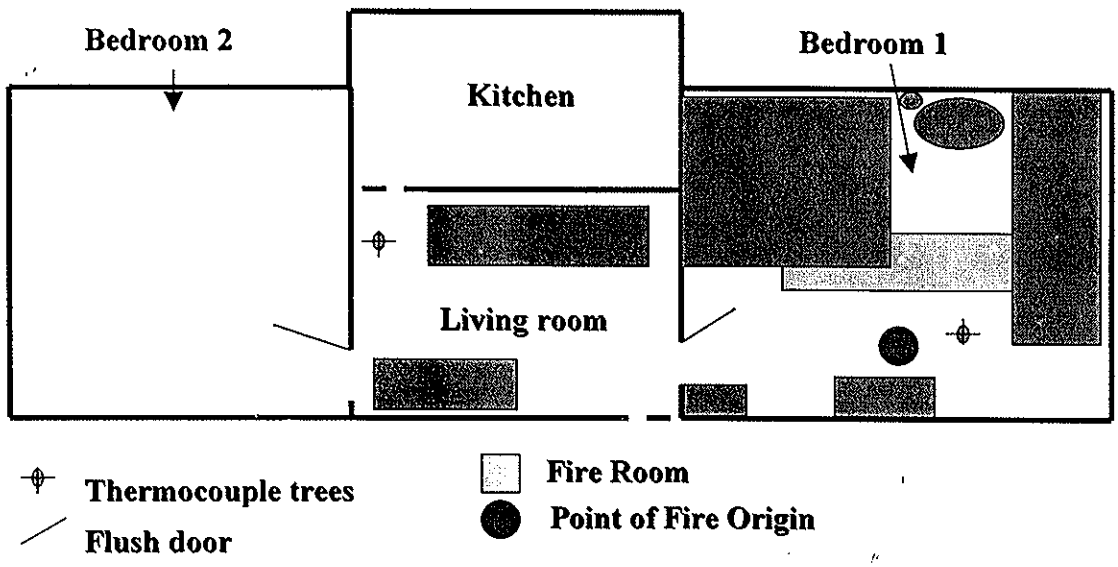




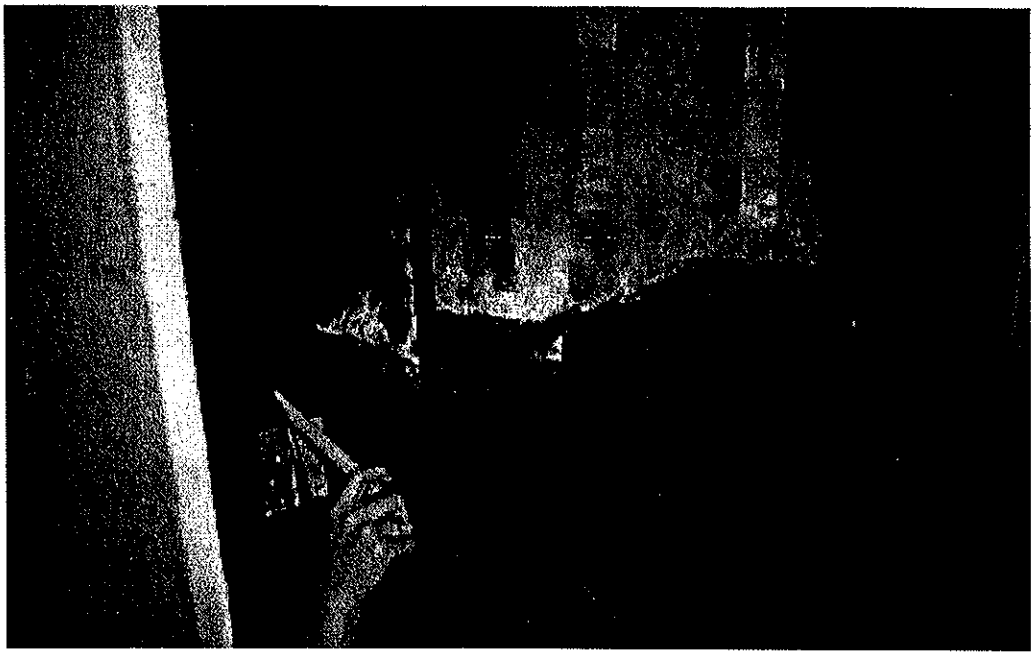


Photographs of the Fire Test conducted at Forfar Square

The burn room (Bedroom 1) was furnished with a queen-sized bed with spring mattress, a timber built-in wardrobe, a PVC foam-padded sofa and some clothing. The instrumentation used for the test include thermocouples and portable CO level detection devices which were employed to record temperatures and CO levels at several intervals. The thermocouples were positioned at 300mm, 600mm, 900mm, 1200mm, 1500mm, 1800mm, 2100mm and 2400mm from the finished floor level of the bedroom upwards toward the ceiling. Physical markings were made on the walls of the adjoining rooms at 300mm intervals to provide measurements of the smoke layer heights over time. A video of the test was taken to capture the early burn room events and to observe the smokey gas flow, including other effects that happened in the residential unit.



Instrumentation Layout at Forfar Square

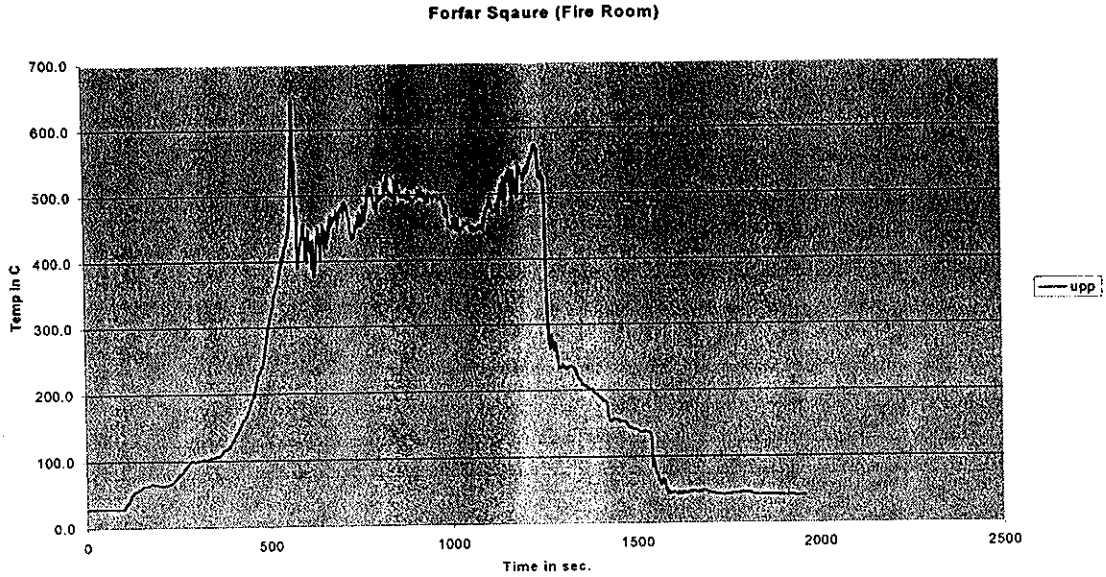


View of Fire Test at Forfar Square

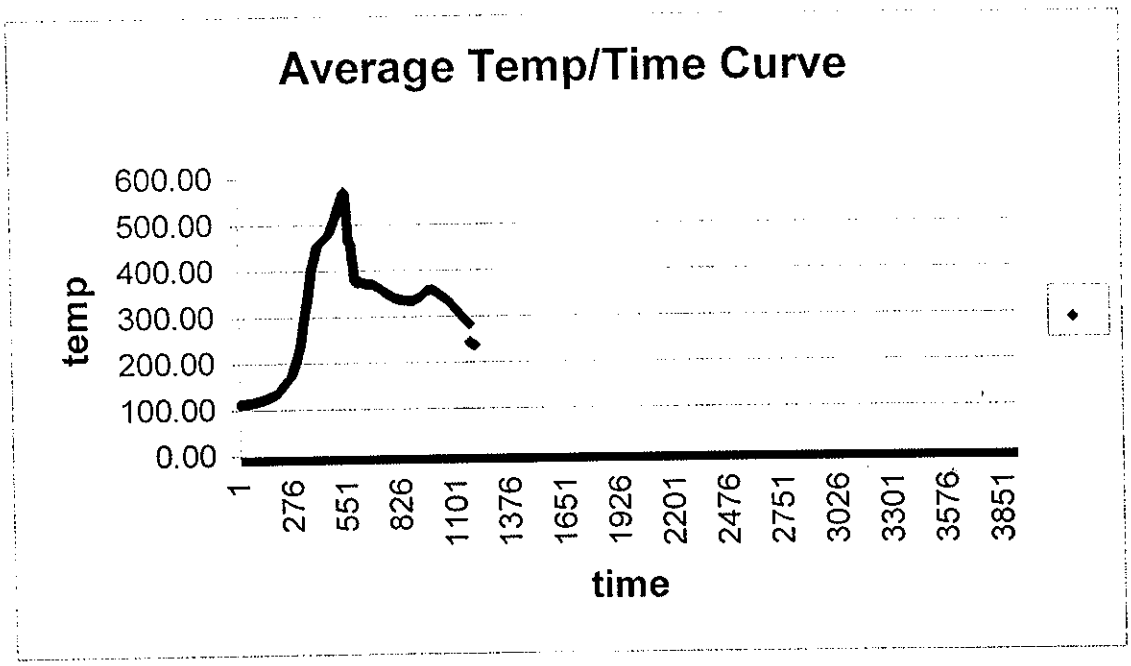
Results of Fire Test 1

The temperatures and amounts of CO recorded at the various intervals of the fire were recorded. The smoke layer heights were also observed.

The results were plotted into line graphs and studied. Generally, the results are indeed consistent with the established theory on fire development and flashover was recorded to have occurred at the 9^{th} minute from the point of first ignition as indicated in the actual temperature-time graph below.



Actual Fire Test Results: Average Upper Layer Temperature over time

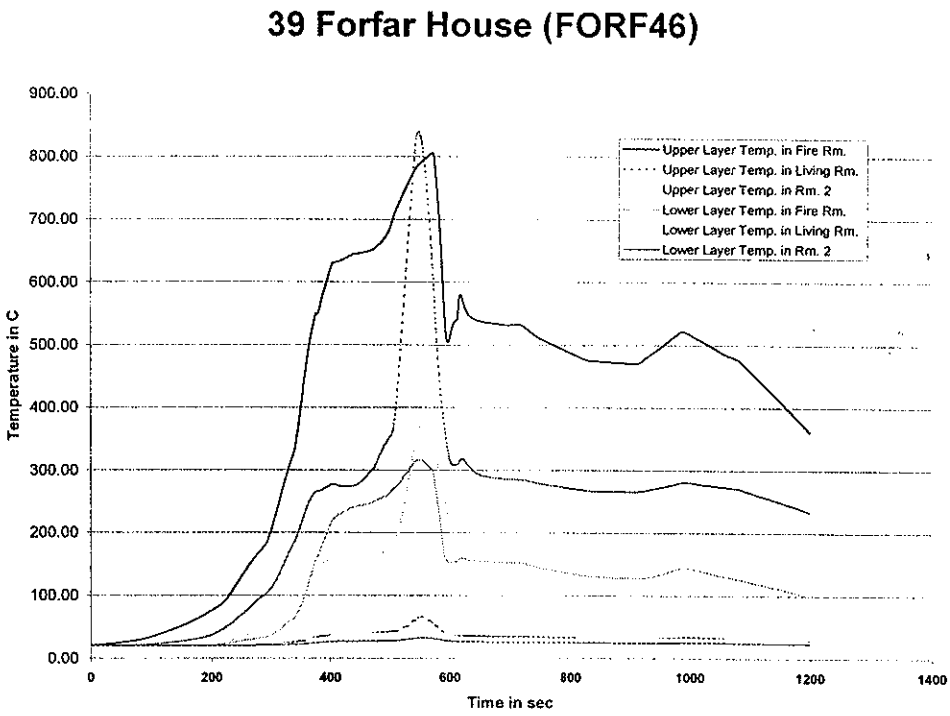


Actual Fire Test Results: Average Room Temperature over time

COMPARISON WITH COMPUTER ZONE MODELING

The real data obtained was then compared with model calculations using FAST. The various parameters set at the full-scale tests were input into the "FAST 3.1.6" model and the resulting predictions were analysed for its accuracy. The fuel and species mass input to the program was specified, along with the dimensions of the fire compartments, connections between them, floor, wall and ceiling materials. The main parameters considered for comparison are:-

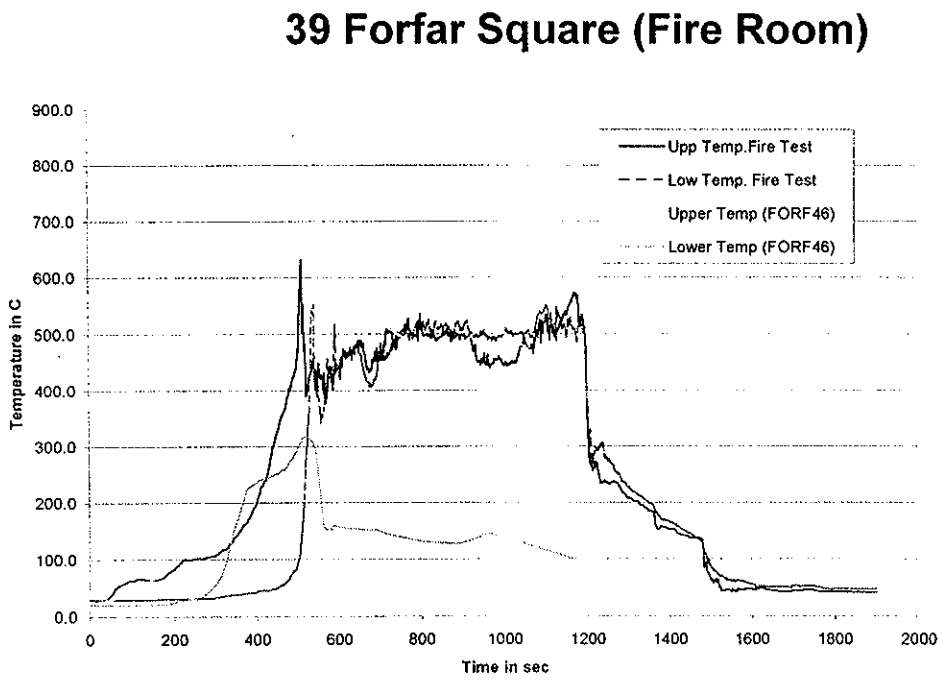
- Temperatures (upper & lower layers);
- Flashover time;
- Smoke Layer heights; and
- Carbon monoxide production.



FAST Simulation Fire Test 1 Results : Simulated Temperature over time

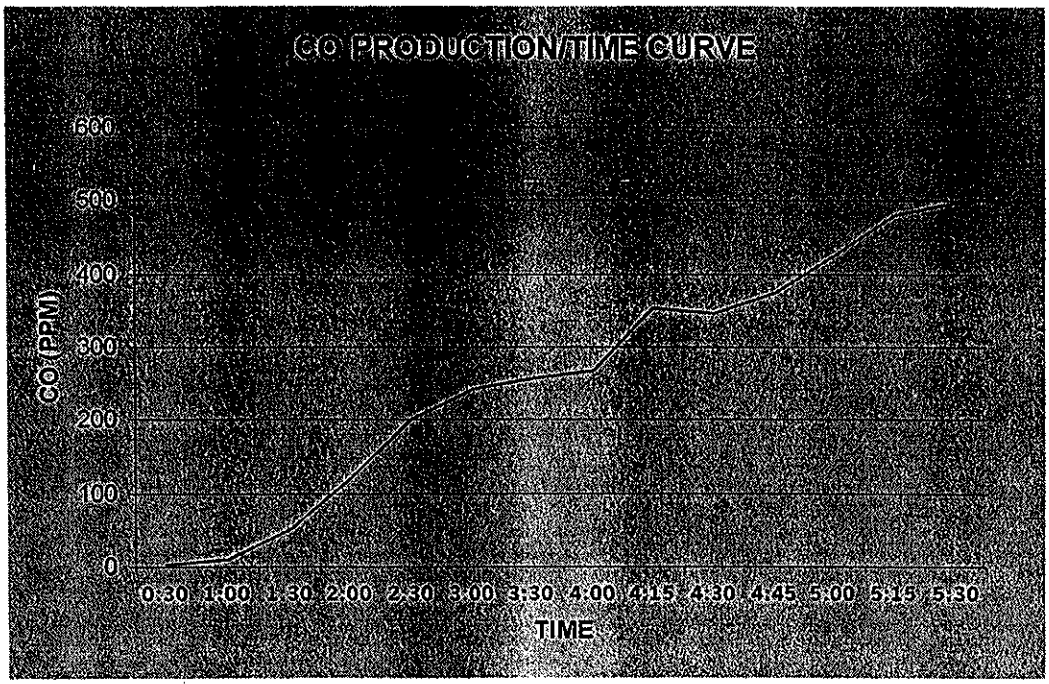
Temperature Measurements (Upper and Lower Layers) and Flashover Time

Upper and lower layer temperature calculations were plotted and these compared with the data from the Fire Test 1 as captured below.



Comparison graph between Measured Data and Computer model

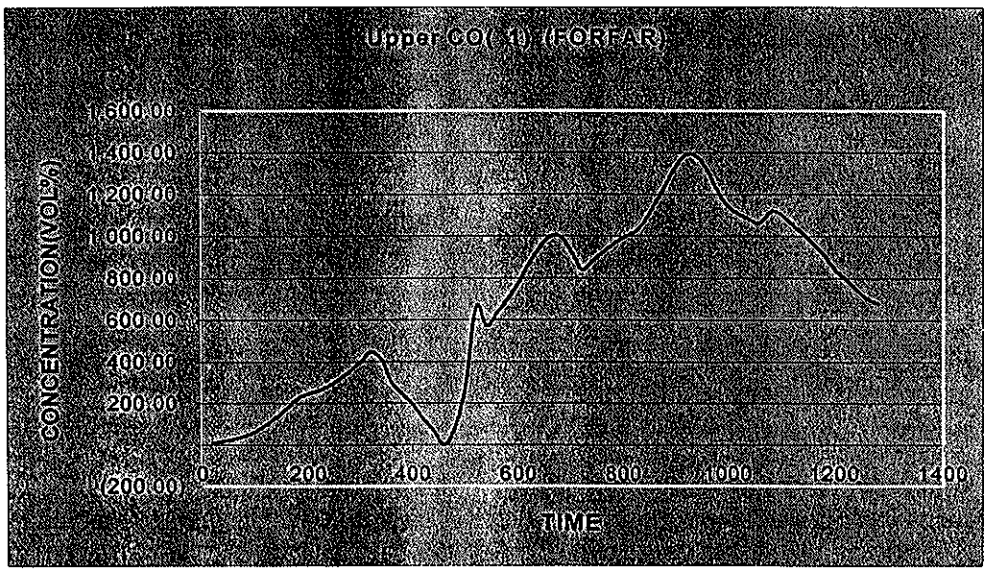
Note that the calculated temperature-time curves start out more rapidly than the real data and there are crossovers in the region 100 to 200 seconds. Examination of the FAST calculation printouts showed that the peak temperature of 570 degree celcius was reached at 543 seconds which closely reflects the real temperature of 631 degree celcius in 509 seconds. The temperature-time curve (flashover) predicted by the model provides a deviation of about -9.6% and + 6.6% respectively. Therefore, the deviation of the simulation results from the real test can be approximated to be about ±10%. This can be attributed to the fact that FAST does not take into account the arrangement of the fuel within the room and makes prediction on fire growth based on layering concept of uniform temperature and pressure throughout the layers.



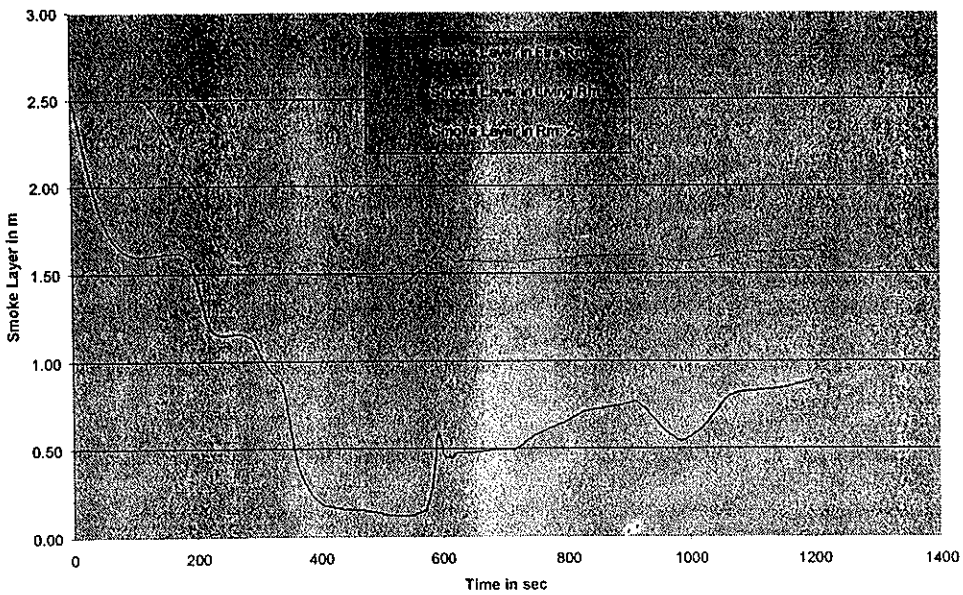
Actual Fire Test 1 Results : Measured CO concentration over time

CO Gas Composition

The CO measurements were recorded at one-minute interval and within the first minute 145 ppm were reached. The CO concentration in the room steadily increased until it reached maximum operating limits of 500 ppm of the portable detectors which were located close to the doorway of the fire room. The maximum was reached at the 8th minute from the initial fire ignition. The results are as shown in the graph above.



A comparison of the simulated results on CO measurements using the FAST model with the real data was done for the time until prior to flashover being reached, due to maximum operating limits of the portable gas detector. Generally, higher concentrations of CO (beyond the operating limits of the detector used) are expected after flashover. More incomplete burning is likely to happen due to oxygen depletion. During flashover, FAST simulates a marked decrease in CO concentrations but this cannot be verified with actual data as it was not obtained during the fire test. However, it can be observed that the FAST outputs for CO concentrations in the first 5 minutes coincides well with the measurements taken during the fire test.



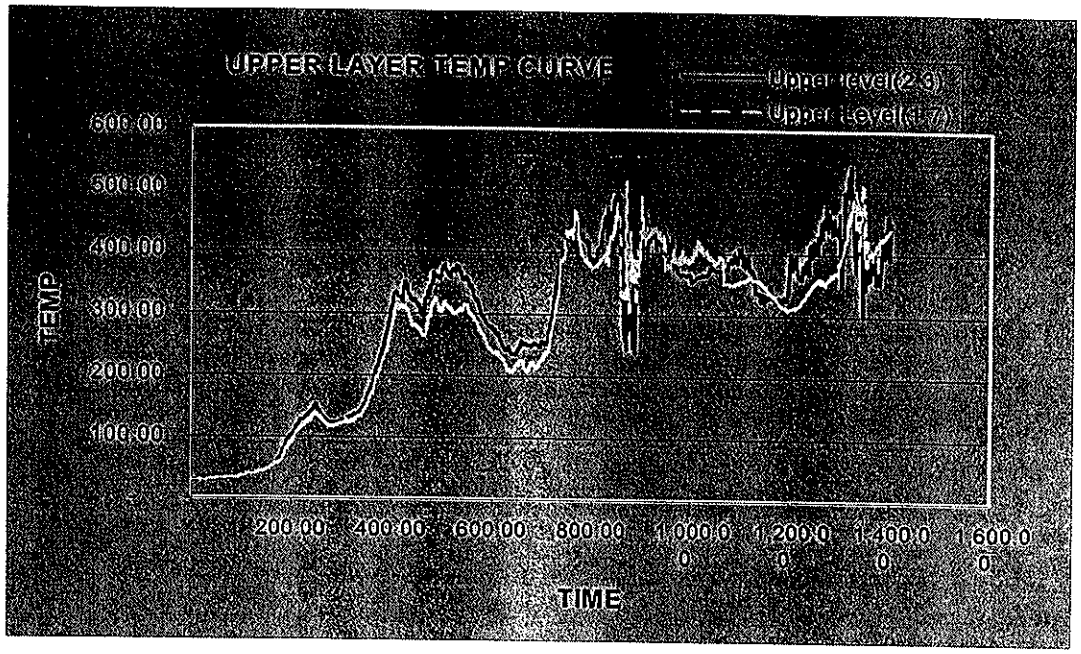
FAST SIMULATION FIRE TEST 1 RESULTS: SMOKE LAYER HEIGHTS VS TIME

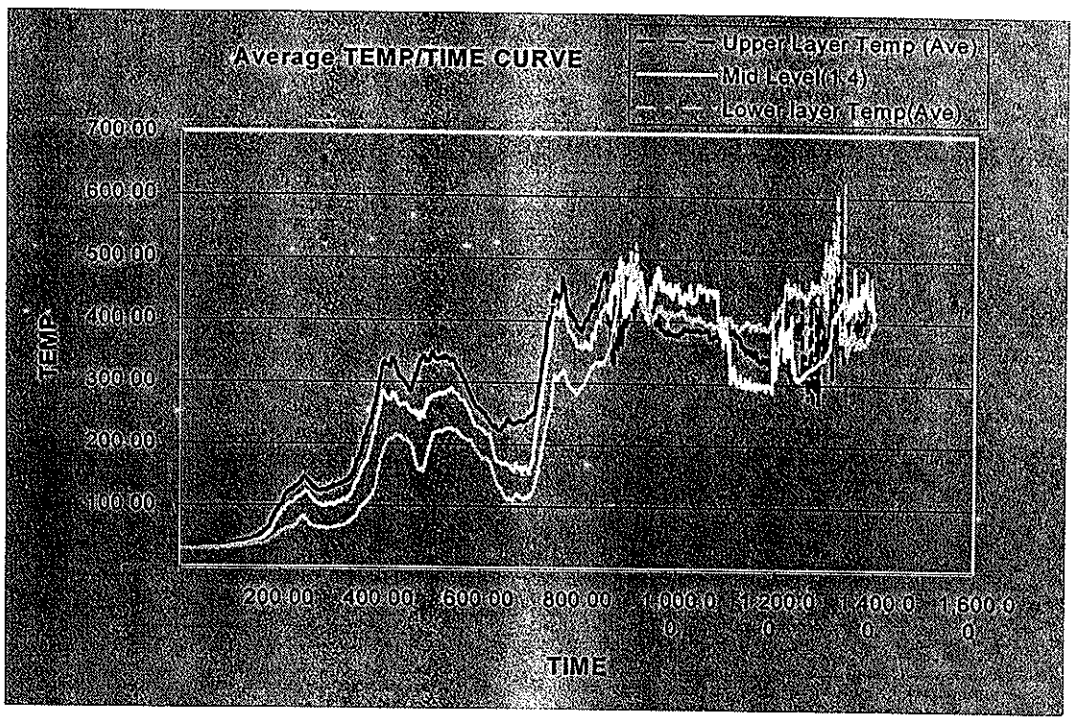
The smoke layer heights predicted by the FAST programme matches well with that observed during the actual fire tests. Soots stained walls of the living and the adjoining room to heights 1.5m above the floor level during the conduct of the fire test.

Results of Fire Test 2

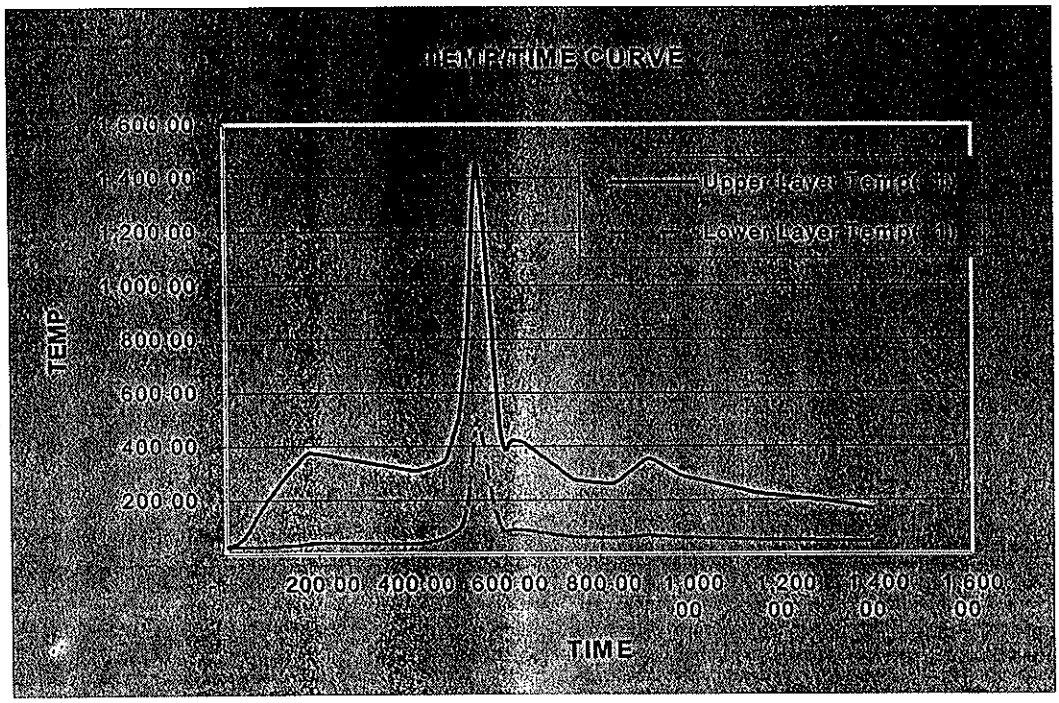
Another similar test was conducted at Blk 110 Depot Road in a 3-room HDB apartment. The temperatures and the smoke layer heights parameters were monitored and recorded using the same instruments and techniques as for the first test.

The results were also plotted into line graphs and compared with the model calculations using FAST. The dimensions of the room keyed in and the fire characteristics of the furnishings taken into account.

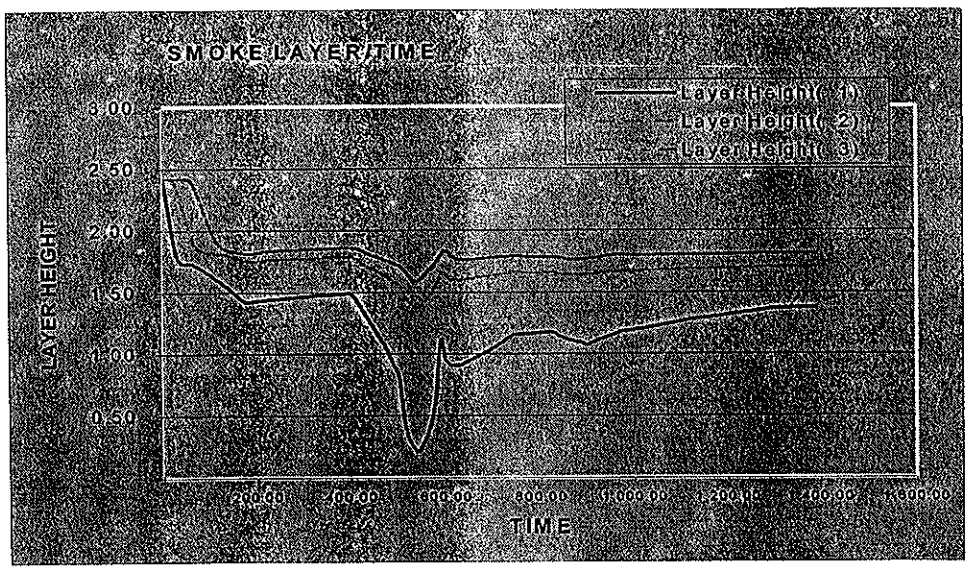




MEASURED FIRE TEST 2 RESULTS : TEMPERATURE-TIME CURVES



FAST SIMULATION FIRE TEST 2 RESULTS: TEMP -TIME GRAPH



FAST SIMULATION FIRE TEST 2: SMOKE LAYER HEIGHT VS TIME

The second test did not reach a flashover situation, likely due to lack of sufficient combustibles. In addition, two thermocouples gave readings that were not consistent with the rest due to failure. The experimental results were somewhat erratic after about 500s when these thermocouples recorded off-readings. As such, the temperatures for the

first 400s prior to if flashover had occurred were compared with the FAST simulation and this showed reasonably close results. For the case of the smoke layer heights observed during the actual test, these matched well with the simulation from FAST.

Limitations of ZONE model

Zone modeling is based on a conceptual representation for the compartment fire process and is an approximation to reality. Any radical departure from the concept of zone model can seriously affect the accuracy and validity of the approach. Therefore, zone models by definition will always be approximate, as it does not see fire as a 3-dimensional phenomenon. The major disadvantage of zone models is that they cannot provide accurate description of compartment flows, temperature distributions, and species concentration. Zone models can typically only predict the average upper layer temperature and species concentration. The fire environment in a room is very complex but zone models tend to depict them as simplistic 2-dimensional models thus contributing to inaccuracy in predicting fires. It provides only an approximation to reality. The other limitations include the following:

a Output predicted by the zone model is only as accurate as the input, especially the input fire.

b Scope limitations such as (1) simplification of assumptions e.g. uniformity of pressure, mass, species and density concentration in an entire layer i.e. the upper and lower layers; (2) see all enclosures as rectangulars, cannot model other shapes; (3) cannot model accurately fires in large spaces, multi-storey buildings, vertical structures such as stairwells, and enclosures with large aspect ratios (e.g. corridors) due mainly to its one dimensional modeling of fires, and its assumption of instantaneous fire spread of smoke over entire enclosure. Typically, limited to compartment size fires of 3 to 5 MW. This is because the plume model in FAST assumes a point source for the fire rather than an extended area of fire. (4) Data limitations as data are collated from furniture calorimeter and enclosure fire tests done overseas, where temperature and ambient conditions are different. Thus, results cannot be taken wholesale for models run outside its country of origin.

c It does not model fire but merely model its effects, i.e. temperature, species concentrations, tenability conditions versus time etc. The fire source is specified by the user, and thus the model may produce physically impossible results if the wrong conditions are specified.

d One cannot use one zone model to test another as both may have similar errors.

Application of Zone Models

Zone models can model a fire environment in a multi enclosure building. It assesses the effects of a change in the system. Not only does it provide information such as occupant evacuation, time to flashover, species concentrations etc which are useful parameters in determining the design of fire safety systems, it also provides and allows for integration of additional components like heat detector response and sprinkler intervention. The zone model can be a predictive tool for small room fires. Applications of modeling encompass the reconstruction of fire incidents, hazard analysis of building materials and contents and evaluation of fire code requirements.

Advantages of Zone Models

The advantages of zone models are as follows:-

a Simplicity

b Reasonable accuracy

c User friendly

d Short computing time

e Inexpensive

f Capable of simulating fire growth and smoke spread in multi-storey buildings and up to 30 enclosures. Zone models predict time-dependent concentration, ventilation rate, radiant heat flux, zone interface height etc.

Conclusion

It is acknowledged that the lessons we learnt from the actual fire test and the model study help us to further pursue how zone models can be used to support the performance-based building designs. Other than this, we also note the reasonable comparison between the measured and modelled results give us a good level of confidence in the model. Since the input fire was built from sources of fire data, and that the modelled results agree with those of a fire test based on realistic fuel load, we are able to establish a fire scenario for future studies in similar residential environment. The agreement between the 2 tests also allow us to assess the fire effects beyond the room of origin as well as in the neigbouring units. The successful establishment of the input fire scenario allows us to model the fire effects under other options of fire safety provisions, as will be essential in the case of performance-based designs. The application in re-constructing fire for investigation purpose is yet another usefulness of zone models.

However, we would also like to emphasise that more studies are required to compare fire tests and model studies so as to enlarge our database in terms of building configurations, occupancy and perhaps other environmental factors (such as wind).

Paper 2

BR 368e : Smoke Ventilation for Atrium Buildings

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BR368e –SMOKE VENTILATION FOR ATRIUM BUILDINGS

Ho Nee Fun
Fire Engineering Technology Centre
Building Department
Ngee Ann Polytechnic

1. Introduction

This software program (BR368e) is written as an aid for designing smoke ventilation systems for atria. It consists of a suite of algorithms on the different smoke ventilation methodologies presented in the guidelines "BR368 – Design Methodologies for Smoke and Heat Exhaust Ventilation".

The program facilitates the users to go through the complete design procedures while allowing options specific for any particular design scenario.

2. Design Methodologies for Smoke and Heat Exhaust Ventilation

This guide summarizes the advice available from the Fire Research Station, to designers of Smoke and Heat Exhaust Ventilation Systems (SHEVS) for atria and other buildings. Its purpose is to provide practical guidance on the design of smoke-control systems.

It reflects current knowledge and is based on the results of research where available, including as yet unpublished results of experiments. In addition, it draws on the authors' cumulative experience of design features required for regulatory purposes in many individual smoke-control applications. Many of these design features have evolved over several years by consensus between regulatory authorities, developers and fire scientists.

The calculations can be done using an electronic calculator having scientific functions. This, however, may be time consuming, particularly where the designer wishes to look at a number of geometries or conditions. The calculations can

easily be incorporated in a computer program where frequent calculations are required.

3. Methods of Smoke and Heat Extraction

The following three methods of smoke and heat extraction are covered by the BR368e software program:-

(i) Ventilation from the room of origin;
(ii) Ventilation from underbalcony smoke reservoir; and
(iii) Throughflow ventilation

3.1 Ventilation from the Room of Origin

Smoke ventilation from the room of origin is a much preferable method to control the smoke in a fire room and hence prevent the spread of smoke to other areas outside the room.

This can be achieved by using a dedicated smoke exhaust system or adapting the ventilating or air-conditioning system. If the room is open to a corridor or/and atrium then it must have either a downstand barrier (Figure 3.1.1) to create a reservoir within the room, or a high-powered exhaust slot (Figure 3.1.2) at the boundary edge to achieve the same effect.

The rate of air entrainment into a plume of smoke rising above a fire, M_f, may be obtained using the equation:-

$$\mathbf{M_f = C_e P Y^{3/2}} \qquad \mathbf{kg/s}$$

where:

C_e = entrainment coefficient

P = perimeter of fire, metre

Y = height of rise of the plume, metre

The mean temperature rise of the smoke layer above ambient, θ, can be calculated from:-

$$\theta = Q_f / M_f c \quad K$$

where:

Q_f = convective heat flux of the fire, kW

c = specific heat capacity of the gases, kJ/kg K

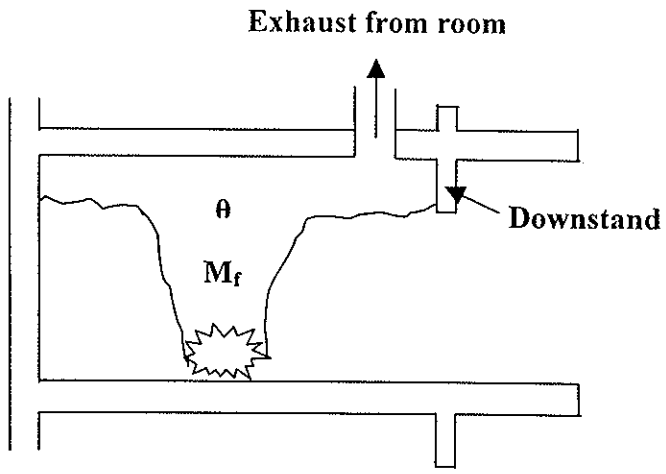


Figure 3.1.1 – Use of a downstand to create a smoke reservoir.

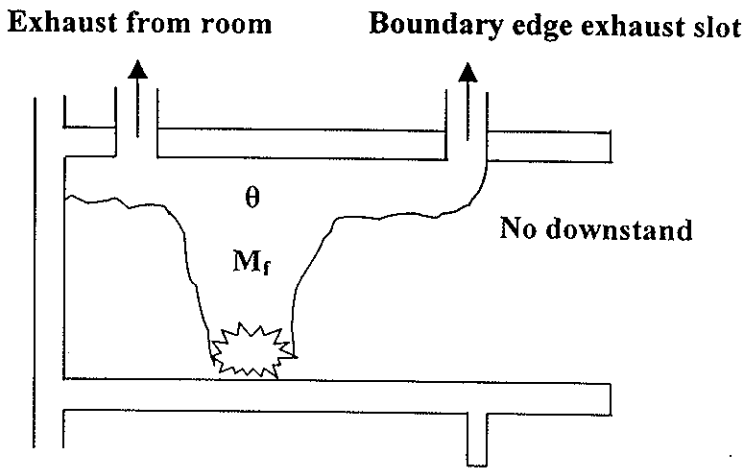


Figure 3.1.2 – Use of a "slot exhaust" to prevent smoke entering the atrium.

3.2 Ventilation from UnderBalcony Smoke Reservoir

If smoke ventilation from the room of origin cannot be achieved because the rooms have demountable partitions, insufficient replacement air can be provided or the engineering implications are too costly or difficult to apply, then the smoke and hot gases can travel beyond the room of origin to the corridor or atrium.

In this instance, we can employ smoke screen at the edge of the balcony which is activated by the smoke detector to create a smoke reservoir under the balcony space. Then we can extract the smoke and hot gases from this underbalcony smoke reservoir (Figure 3.2).

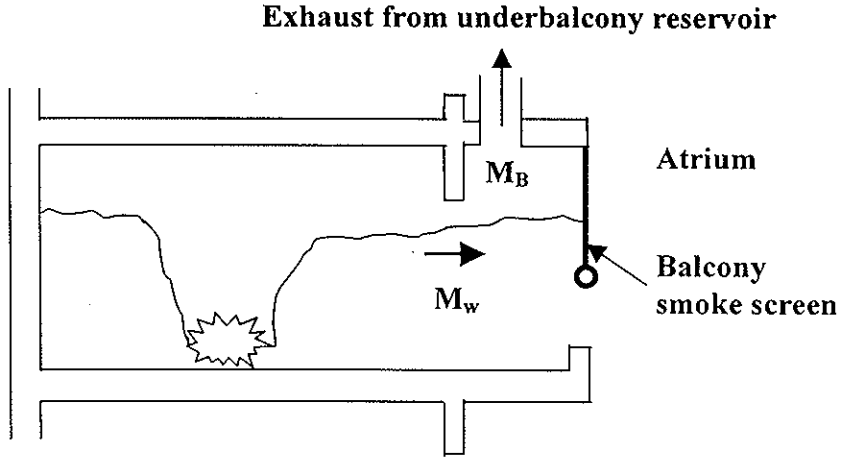


Figure 3.2 – An underbalcony smoke reservoir.

The mass flow rate of smoky gases passing through a vertical opening, M_w, may be found from this equation:-

$$M_w = \frac{C_e P W h^{3/2}}{[W^{2/3} + (1 / C_d) (C_e P / 2)^{2/3}]^{3/2}} \quad \text{kg/s}$$

where:

W = width of opening, metre

h = height of the top of opening above the floor, metre

C_d = effective coefficient of discharge for the opening

In the continuing absence of better evidence, the Fire Research Station suggests that for the purpose of engineering design (further research is highly desirable) the mass flow rate of smoke entering the balcony reservoir, M_B can be taken to be approximately as:-

$$M_B = 2\, M_w \quad \text{kg/s}$$

3.3 Throughflow Ventilation

If the smoke and hot gases cannot be extracted from the room of origin or underbalcony reservoir, then the use of "throughflow" ventilation from the atrium itself is usually considered (Figure 3.3).

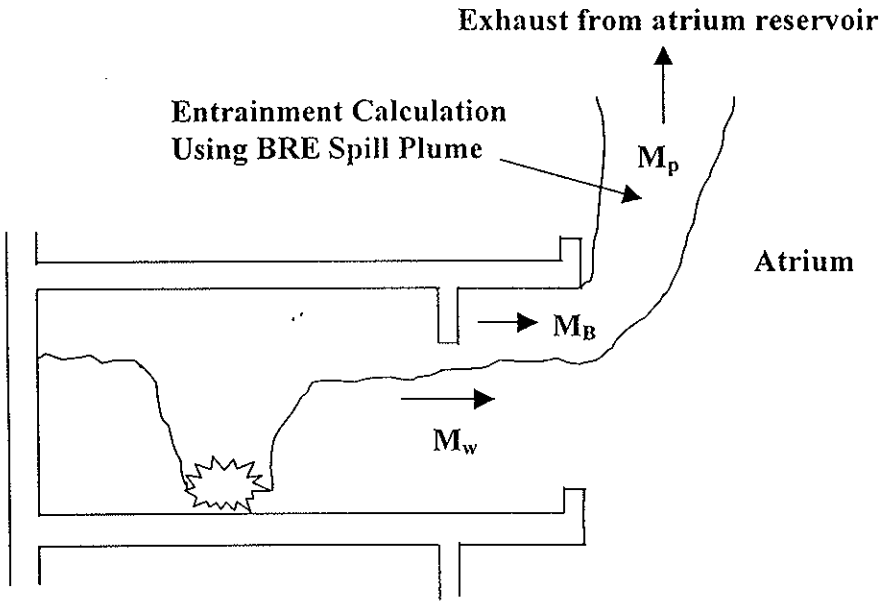


Figure 3.3 – Throughflow Ventilation

4. Minimum Number of Extraction Points

The number of exhaust points (N) within the reservoir is important since, for any specified layer depth, there is a maximum rate (M_{CRIT}) at which smoky gases can enter any individual exhaust point.

The critical exhaust rate, M_{CRIT} for a ventilator away from a wall is given by:-

$$M_{CRIT} = \frac{2.05\ \rho_o\ (g\ T_o\ \theta_l)^{0.5}\ D^2\ W_v^{0.5}}{T_l} \quad \text{Kg/s}$$

where:

ρ_o = density of air at ambient temperature, kg/m^3

g = acceleration due to gravity, m/s^2

D = depth of smoke layer below the exhaust point, m

T_o = absolute ambient temperature, K

θ_l = excess temperature of smoke layer, °C

$T_l = T_o + \theta_l$ K

W_v = characteristic width of the ventilator, m (eg the diameter)

For ventilators which are close to walls, the critical exhaust rate, M_{CRIT} is given by:

$$M_{CRIT} = 1.3 \left(\frac{g D^5 T_o \theta_l}{T_l^2} \right) \quad kg/s$$

The required number of extract vents, N is then given by:

$$N \geq \frac{M_e}{M_{CRIT}}$$

where:

M_e = mass flow rate entering the layer i.e. M_f or M_B or M_p, kg/s

5. Area of Natural Ventilation Required

A natural ventilation system uses the buoyancy of the smoke to provide the driving force for exhaust. The rate of exhaust is largely dependent upon the depth and temperature of the smoke.

The precise relationship between the mass flow rate extracted, the ventilator area, the inlet area and the smoke layer is given by:

$$M_l = \frac{\rho_o A_v C_v (2g D \theta_l T_o)^{1/2}}{[T_l^2 + (A_v C_v / A_i C_i)^2 T_o T_l]^{1/2}} \quad kg/s$$

It can be re-arranged algebraically into the more convenient form:

$$A_v C_v = \frac{M_l T_l}{(2g \rho_o^2 D \theta_l T_o - [T_l T_o M_l^2 / A_i^2 C_i^2])^{0.5}}$$

where:

A_v = measured throat area of ventilators, m^2

A_i = total area of all inlets, m^2

C_v = coefficient of discharge (usually between 0.5 and 0.7)

C_i = entry coefficient for inlets (typically about 0.6)

M_l = mass flow rate of smoke to be extracted, kg/s

D = depth of smoke beneath ventilator, m

ρ_o = ambient air density, kg/m^3

g = acceleration due to gravity, m/s^2

θ_l = temperature rise of smoke layer above ambient, °C

T_l = absolute temperature of smoke layer, K

T_o = absolute temperature of ambient air, K

6. Required Ventilation Rate (Powered Exhaust)

A powered smoke exhaust system consists of fans and associated ductwork designed to remove the mass flow rate of smoke entering the smoke reservoir, and to be capable of withstanding the anticipated smoke temperatures.

The volumetric flow rate for the selection of the appropriate fans is given by:

$$V_l = (M_l T_l) / (\rho_o T_o) \quad m^3/s$$

where:

V_l = volumetric exhaust rate required in the reservoir, m^3/s

$M_l = M_f$ or M_B or M_p, kg/s

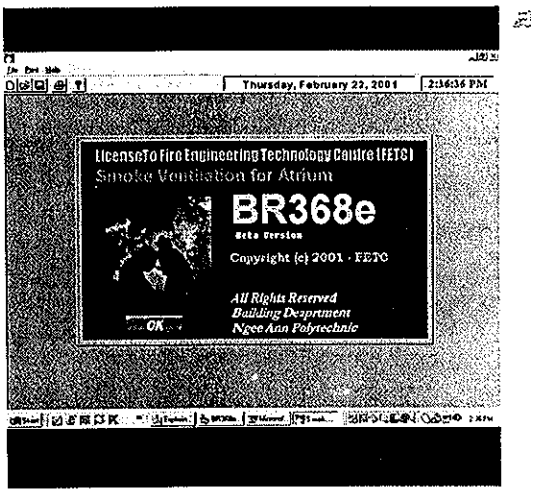
T_o = ambient air temperature, K

$T_l = T_o + \theta_l$, K

ρ_o = density of ambient air,kg/m^3

7. BR368e – Smoke Ventilation for Atrium Buildings

Demonstration of BR368e software.



8. References

[1] H P Morgan, B K Ghosh, G Garrad, R Pamlitschka, J-C De Smedt, L R Schoonbaert, Design Methodologies for Smoke and Heat Exhaust Ventilation, British Research Establishment / Fire Research Station, Construction Research Communications Ltd, London, UK, 1999.

[2] Wong Kin Man, BR258e Software, 1999.

[3] G O Hansell, H P Morgan, Design Approaches for Smoke Control in Atrium Buildings, British Research Establishment, Garston, Watford, UK, 1994.

[4] Gary Cornell, Visual Basic 6 from the Ground Up, McGraw-Hill Companies, United States of America,1998.

[5] David I Schneider, An Introduction to Programming Using Visual Basic 6.0, 4th Edition, Prentice Hall, New Jersey, 1999.

[6] John Cowell, Essential Visual Basic 6.0 Fast, Springer-Verlag London Limited, Great Britain, 2000.

[7] Shimon Mordynski, Lowell Mauer, How to use Visual Basic 6.0 (Visually in Full Color), Sams Publishing, United States of America, 1999.

Paper 3

Development and Use of Fire Models :

The Australian Experience

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Ove Arup & Partners

DEVELOPMENT AND USE OF FIRE MODELS -

THE AUSTRALIAN EXPERIENCE

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1 INTRODUCTION

The growth of fire engineering design of buildings, transport infrastructure and industrial buildings in Australia and internationally has led to the increasing use of fire models. These models can be used for egress analysis, smoke filling analysis, structural performance under fire, and many other forms of evaluation.

Models are important tools for fire safety engineers but do not replace clear understanding of fire safety principles, engineering judgement or solve all problems of design. In many cases, simple hand calculations based on well founded equations can be used for design. However, the models are becoming increasingly sophisticated and there is an on-going need for education of fire safety engineers and approval authorities in the use of models.

This paper looks at the use of fire models set in the context of the transition to performance based design and building regulations in Australia over the past 10 years.

2 BACKGROUND

Until the last decade, most countries including Australia had building codes and fire regulations that were prescriptive, inflexible, not consistent and often expensive to implement.

In the 1970's, Australian fire engineers such as Laurence Reddaway advocated more rational engineering approaches to building fire safety design. In the 1980's, Professor

Vaughan Beck from Victoria University of Technology demonstrated the benefits of risk assessment as the basis for more cost effective building regulations and fire safety. The movement was given major impetus through a high profile fire engineering project conducted at the Warren Centre for Advanced Engineering, University of Sydney in 1989. The Warren Centre targets key industry sectors that have the potential to make a paradigm shift as a result of a six month research effort. Professor Vaughan Beck was the Visiting Fellow for the fire engineering project. Working with some 70 of Australia's best building, design and fire safety professionals, Professor Beck's 'Warren Centre Project" showed that rational performance based building regulations and fire safety engineering methods were likely to save Australia some A$200 million annually in construction costs.

This thrust was continued with the Government supported Building Regulation Review Task Force (BRRTF) in 1991 which funded the development of the risk based draft "National Building Fire Safety Systems Code", a world first in terms of measuring levels of fire safety in buildings.

The clear benefits of an engineered, performance based approach led the Commonwealth Government to set up the Australian Building Codes Board (ABCB) in 1994. Their express charter was to develop the framework and model Building Code of Australia (BCA) which would allow performance based fire safety design.

At the same time it was recognised that a good deal of research was required to provide the technical tools and design methodologies to ensure the success of performance based fire safety design. So in 1994, key participants in the Warren Centre and BRRTF fire safety activities formed the Fire Code Reform Centre (FCRC), a not-for-profit company. The FCRC charter was to solicit funds from government and industry and allocate these funds to Australia's leading fire research and engineering groups in a targeted coordinated research program. A $7.5 million research program is in progress.

The ABCB produced the performance based BCA in 1996, which was adopted into legislation by all States of Australia in 1997. The FCRC produced the "Fire Engineering Guidelines" which has been accepted in Australia and widely acknowledged internationally as the state of the art in fire safety design methodologies.

At the same time, fire engineering training for all sectors of industry, changes in liability law, introduction of professional registration and private certification or approval practices have all been part of a major reform of building fire safety design in Australia.

The results of this holistic program of reform in Australia has been:-

- Better, more functional buildings.
- More flexible designs.
- Strong support for innovation.
- Equal or better life safety.
- More cost effective buildings.
- A more internationally competitive construction industry.

A key part of this reform and the benefits which have flowed come from fire safety engineering and the use of models as part of the analysis required to substantiate Alternative Solutions to the prescriptive requirements of the Building Code of Australia.

3 FIRE MODELS

A fire model is a tool available to the fire safety engineer to predict fire behaviour and the impact of a fire on the surrounding environment. Bukowski[1] defines fire models as "Fire models attempt to represent the way fires progress by including mathematical descriptions of the important physics and chemistry of the process.".

There are many fire models and methods of predicting fire behaviour available to fire safety engineers in Australia. These can be divided into two main categories, namely hand calculations and computer models.

Hand calculation models

Hand calculations are based on equations derived from theoretical relationships as well as relationships found in experiments and test data. These equations may involve, for example, mass entrainment into a fire plume, heat development in a smoke layer and radiation emitted from a fire source. Relationships may be combined to create a series

of events and to get a time sequence of certain events, which can easily be presented for checking and approval by authorities.

Documents that are widely used throughout Australia include:

- The Fire Engineering Guidelines[2]. This Australian document contains calculation methods and design guidance for most events associated with fire and fire development. It also gives an extensive description of the fire safety design process and the different levels of performing a quantified analysis. It includes information such as reliability of fire safety systems, fire brigade intervention, life safety criteria and occupants characteristics. The Fire Engineering Guidelines is currently being updated and divided into three parts, namely methodology, design methods and data.

- The SFPE Handbook of Fire Protection Engineering[3] is a very extensive document specifically developed for the Fire Engineering discipline. It presents theoretical background and derivations of most relationships and models used throughout the world. Sections of this document that are commonly used in Australia are those addressing evacuation and occupant behaviour, design of detection systems, structural adequacy during fire exposure and burning rates of different materials. The Handbook also contains detailed sections of fire dynamics and fundamental physics, chemistry and dynamics.

- An Introduction to Fire Dynamics[4] is the most thorough document addressing the phenomena associated with fire science and fire dynamics. It reports on the scientific background, including theoretical relationships as well as experimental tests, necessary for fire safety engineering and can be used as design guidance for many applications of fire safety. Some especially useful sections include those on heat transfer, pre- and post-flashover compartment fire and production and movement of smoke.

- CIBSE Guide E[5] provides methods and information of how to determine occupant evacuation times, formation of smoke layers and other fire dynamics relationships,

design of fire safety systems such as sprinkler systems, smoke ventilation systems and fire alarm systems.

- NFPA 92B[6]is a good reference that can be used to determine smoke development, smoke layer formation and smoke ventilation requirements.

Other hand calculation models that are used in a performance based design environment include, for example, papers presented at conferences and in fire engineering journals, various research reports and design guides. Other useful documents are Design of Smoke Management Systems[7], Fire Safety In Shopping Centres[8] and Enclosure Fire Dynamics[9]. Australian Standards may also be used for some applications such as determining the adequacy of a structural member exposed to fire conditions.

Hand calculations models vary in complexity and range from simple equations containing one variable or input, to extremely complex differential equations with many variables that only can be solved via finite difference methods. The former allows the fire safety engineer to conduct quick preliminary predictions of for example smoke exhaust requirements and separation distance between buildings. The latter is very time consuming and urges the use of more sophisticated and high processing models, such as computer models.

3.1 Computer models

The computer fire models of today are able to process a scenario in a time efficient and easily interpreted way. Fire models are used by a wide range of professions such as building designers, approval authorities, researchers and by specialists in court cases.

Computer fire models commonly used within the fire engineering discipline involves computer software for predicting heat development and smoke logging in a compartment fire, radiation emitted from a fire, detector activation time and heating of structural elements. In a very simplistic way, computer fire models can be described as processing a large number of equations and relationships combined to describe a fire scenario in an as realistic way as possible. Given certain conditions or change of conditions, the equations can be combined in different ways to achieve an outcome for

that specific set of input parameters. For example, vents can be opened or closed at certain times or conditions and a fire can become ventilation controlled when not enough air/oxygen is supplied.

In the past, the most commonly used methodology for predicting heat and smoke development and smoke movement in a compartment is the so-called zone modelling[10]. This method is based on the compartment being divided into one upper and one lower zone where the conditions within each zone are homogenous. Using the laws of conservation heat and mass, this approach allows the amount of smoke, temperature etc within each zone to be determined, which also may involve heat transfer to bounding construction. A hypothetical fire is simulated by theoretically and experimentally derived relationships for combustion, heat and smoke generation, mass entrainment and smoke density. Since this method only involves solving equations between two zones and that the zones can be represented by a single value for each property, the fire model is very fast to run and are generally relatively user-friendly. A problem with the zone models is whether two zones actually are formed in special buildings such as atria, stair shafts, corridors, tunnels and large enclosed spaces[11]. In some cases, injection of substantial airflows into the upper layer, non-rectilinear geometry and external wind pressures may mean the use of 2-zone models is inappropriate.

Field models solve fundamental equations for mass, momentum and energy. The space is divided into a very large number of elements and the equations are solved in three-dimensions, which allows the physical conditions within each element to be determined as a function of time. This is the same methodology used in computational fluid dynamics (CFD), ie solving fundamental partial differential equations of mass, momentum and energy. This approach is used in other fields than fire engineering such as aeronautics, mechanical engineering and environmental engineering. Due to the large number of calculations required and the detailed solution produced, the use of field models is very time consuming and requires computers with fast processors and large memory capacity. The field models can determine a variation in conditions within the smoke layer and it has been demonstrated that the models can predict velocities and temperatures with an adequacy of better than 10%[12].

Field models are especially useful in complex spaces such as atria, tunnels and multi-compartment spaces where difficult airflow conditions, wind pressures or other conditions make prediction difficult.

A brief summary of computer fire models and their applications in Australia is presented below.

- **FIRECALC** – A fire model containing a collection of 24 sub-models that have been developed by CSIRO in Australia. The different sub-models can be used to determine smoke logging and temperatures in one- and two-room compartment fires, smoke flow through openings, fire duration and time to flashover. FIRECALC also contains a useful program for determining levels of radiant heat emitted from a fire source. With regard to performance based design, FIRECALC can be used to predict time to untenable conditions within a compartment, design size and exhaust capacity of smoke vents, required fire resistance level of structural members and separation distance between buildings sufficient to prevent fire spread.

- **FAST** – FAST is a multi-compartment zone model that incorporate features such as mechanical ventilation, openings and closing doors, exterior and interior pressure, heat transfer to bounding structure etc. The model is very user-friendly and can be used to predict smoke filling and smoke movement, visibility, smoke layer temperature and required smoke ventilation capacity. The model also contains some sub-models similar to those in FIRECALC.

- **Detact-T2 and Detact-QS** – These two models is useful to predict time to activation of heat detectors and sprinklers. Using crude assumptions, they can also be used to determine time to activation of smoke detectors.

- **TASEF2** - TASEF2[13] is a two-dimensional heat transfer program that can be used to determine adequacy of a structural member. This program has been well validated internationally and is specifically written to analyse configurations involving steel and concrete in fire. An advantage with the program is that fire temperatures derived

from first principles can be used instead of the standard time-temperature relationships used in most hand calculation methods.

- **Simulex** – Simulex is a program used to predict evacuation times from a building. It uses the actual drawing of the building is based on occupant characteristics and behaviour observed in real life situations. The desired number of occupants can be placed throughout the building, occupants can be given a specific properties, eg travel speed and designation to certain exits, and queuing at narrow passages can adequately be predicted. An advantage with the program is that the evacuation simulations are graphically displayed, which is very helpful to for example identify areas where long queuing is likely to occur and where extra exit width may be required.

- **Fire Dynamics Simulator (FDS)** – FDS is a computational fluid dynamics (CFD) fire model of fire-driven fluid flow. The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The model was originally designed to analyse industrial scale fires, It can be used reliably when the fire size is specified and the building is relatively large in relation to the fire. In these cases, the model predicts flow velocities and temperatures to an accuracy of 10 to 20% compared to experimental measurements[14].

The figure below demonstrates how some of the fire models described above can be used to form a life safety analysis of a specific building.

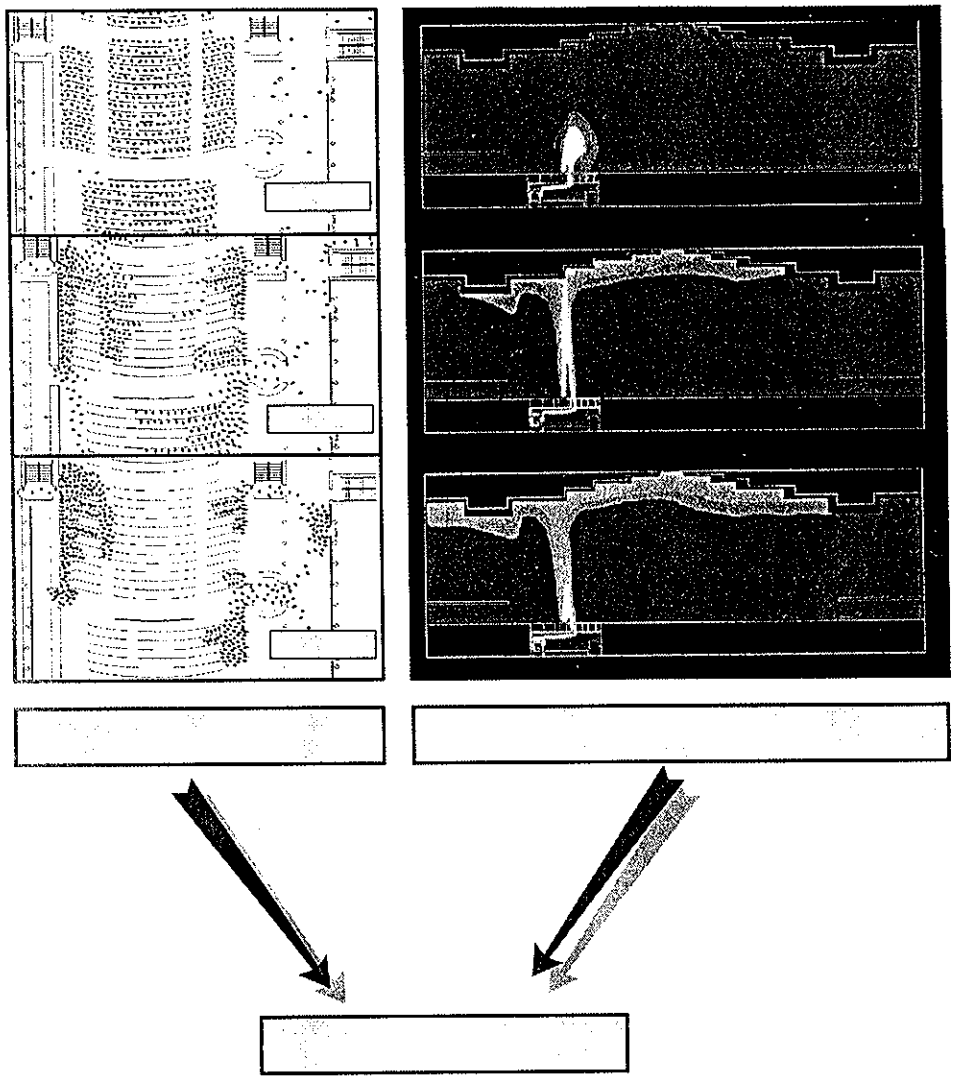


Figure 1 : Evacuation analysis using SIMULEX and prediction of smoke development using field model

3.2 Validation

In order to obtain reliable results, it is extremely important that the fire model has appropriate validation for its specific application. This is achieved by a series of reviews and checks[15], including:

1. Review of the theoretical basis, including chemistry and physics, of the model. It is important that the review also includes the documentation of the models as well as assumptions, approximations and accuracy of the model[2].

2. Numerical tests using hand calculations to check the function of the model.

3. Comparison with other fire models. This comparison is especially beneficial if the other model already has undergone a validation check.

4. Comparison with fire tests and test data. Realistic small and full scale fire tests can be used to investigate if the model is adequate for its intended use. It is however important to account for uncertainties in test measurements and equipment. When the model agrees with the tests, with a wide range of conditions, confidence in validity would be substantial.

It should be noted that a fire model will never produce exact results of a fire scenario. Errors will occur due to for example not having exact input data, models not being used within its limitations and assumptions made by the user of the model. All results and outputs should therefore be critically reviewed.

4 GUIDANCE ON THE USE OF MODELS

How to use computer fire models is generally thoroughly described in the User's Manual accompanying the model. However, as the model is being used in its application, areas are often found where the model is not producing accurate results or where the model has to be used in a certain manner. Such areas may be identified when the model is compared to experimental test results or when extreme results are produced under conditions that are considered as relatively normal. Numerous papers, research reports and other documents are therefore frequently produced around Australia and throughout the world where limitations and guidance on the use of fire models are given.

It is extremely important that model inputs are as accurate as possible. Since uncertainties are very often built into the model, a small deviation input data may yield an incorrect result that in the worst case is unconservative.

For example, the Fire Engineering Guidelines[2] sets out issues which designers and approval authorities should be aware of when zone models are used.

They are:-

- basic physics / plume equation
- enclosure aspect ratio limitations
- limitations on enclosure height and floor area / volume
- limitation on fire size (heat release rate)
- effects of building air conditioning systems
- whether the axisymetric plume assumption holds or not
- are zone model input date conservative
- verification against experimental fire data
- numerical accuracy of results
- uncertainty of results.

5 EXPERIENCE WITH APPROVAL AUTHORITES AND PEER REVIEW

5.1 General

The experience with approval authorities in reviewing fire engineering reports based on fire modelling is variable around Australia. The major limitation is the level of education and training of Fire Brigade and council building surveyors.

In Victoria, all building surveyors undertaking building approvals for performance based designs must be certified as having completed a 1 year part time Graduate Certificate in fire safety engineering. This course gives them a basic understanding of fire engineering principles and fire modelling which assists in their evaluation of designs submitted.

In NSW, there is an accreditation scheme for building certifiers who again must have had the requisite training and experience before approving performance based designs.

Other states are only now getting around to introducing accreditation schemes and the education and training of building surveyors is often insufficient for them to properly review and approve complex performance based designs.

In this situation, where approval authorities have insufficient experience to review fire engineered projects with complex modelling, peer reviews are increasingly being used around Australia, and particularly in New Zealand. A couple of case studies illustrate this point.

5.2 Casino, WA

In Perth, Arup Fire has been involved in the fire safety engineering of a major extensions to a Casino. This has involved extended travel distances, fire engineered smoke control, layer compartment sizes and use of compartment separating elements and structure with a fire resistance level (FRL) less than required under prescriptive guidance. This building also has a large population to evacuate in the event of fire.

Fire models have been used to assess:-

- time to detection (DETACT)
- time to operation of sprinklers (FIRECALC)
- time for smoke filling of compartments (CIBSETM19, FAST)
- time for egress (SFPE Handbook Calculations, SIMULEX)

The building approval authorities felt that they had insufficient experience to deal with such a large, complex building which had extensive performance based design for fire safety. They asked for a peer review, and another fire consultant from Sydney was appointed to review our design at various stages through the project.

The peer reviewer provided initial comment on our Fire Engineering Design Brief (FEDB) report, querying assumptions, design fires, fire models to be used and the input data required.

As the final fire engineering report and the full analysis was completed, the peer reviewer again had input, checking the design solutions, calculations and fire modelling results.

The approving council felt they benefited from this peer review by another fire engineering consultant.

5.3 Rail Station, NSW

In Sydney, Arup Fire has been the peer reviewer for fire engineering of a major underground rail station which is being designed by another leading fire safety consultant.

This 2 track / 2 platform station, which forms part of a new underground rail network, requires smoke control and a somewhat novel natural ventilation system is proposed. There are tunnels at each end of the station and the tunnels and stations need to be

integrated in terms of fire safety design to ensure safe evacuation of passengers under all circumstances.

This project is generally designed to follow NFPA 130 and the NSW Rail Fire and Life Safety Guidelines.
Extensive modelling is proposed for this project, including the use of zone models, the new FDS package and CFD modelling using phoenics.

Clearly this extent of smoke modelling is beyond the skill level of many approval authorities and Arup Fire is working closely with the design team to ensure the models used, input data, result derived, etc. are accurate and meaningful.

6 LATEST RESEARCH AND DATA

A range of organisations are or have been actively involved in fire research and engineering in Australasia including:

- CSIRO Division of Building Construction and Engineering
- Victoria University of Technology (VUT)
- Scientific Services Laboratory (SSL)
- Warrington Fire Research (WFR)
- Building Research Authority of New Zealand (BRANZ)
- BHP Melbourne Research Laboratories

Much of the research has been funded and co-ordinated by the Fire Code Reform Centre(FCRC). This has provided considerable new experimental and other data to verify various models and use as input data to fire modelling for projects.

Examples of the FCRC reports include:-

- FCRC – TR 98-05-"Reliability of Stair Pressurization and Zone smoke Control Systems"
- FCRC – PR 96-03 "Fire Resistance and Non-Combustibility".

- FCRC – TR 96-07 "Flashover Fires – An Experimental Program".
- FCRC – TR 97-12 "Response in Fires Database"
- FCRC, Project 6 "Simulated Shopping Centre Fire Tests".
- FCRC – TR 96-02 "Building Fire Scenarios – An Analysis of Fire Incident Statistics".

Copies of these reports are available from the Fire Code Reform Centre in Sydney. Another organisation which has sponsored considerable research in Australia over the past few years is the Building Control Commission (BCC) in Victoria. Two examples of their work, which provides considerable information for designers and approval authorities on modelling and data, are:-

(i) "Guide for the Design of Fire Resistant Barriers and Structures"; - August 2000.

This research and report prepared by Warrington Fire Research looks at methods to predict the likely exposure of barriers and structures to fire, and by indicating how to assess their performance. It also includes advice on the selection of appropriate test methods and use of test data provided, as well as applications and data from recent research.

(ii) "Research into Cost-Effective Fire Safety Measures for Residential Buildings, Beever, P, Britton, M, February 1999.

This research was undertaken by specialists at Victoria University of Technology. It examines the cost effectiveness of fire safety measures in one and two family dwellings after examining data from approximately 32,00 fires in residential properties. Nine full scale fire tests were also conducted and there is a good deal of data provided which could assist residential property designers.

7 CONCLUSIONS

The use of fire models forms an important role in fire safety engineering design form buildings.

These models need to be used carefully and within their limitations and validation. A good deal of research has been undertaken over the past few years to develop new design methods and models and to generate data suitable for model input.

Education and training of designers, approval authorities and peer reviewers is essential to ensure models are properly utilised for good fire safety design.

8 REFERENCES

1. Bukowski, Richard W., *Fire Models*, NFPA Journal, pp 61-68, March/April 1991
2. Fire Code Reform Centre, *Fire Engineering Guidelines*, Sydney, Australia, March 1996
3. National Fire Protection Association, *The SFPE Handbook of Fire Protection Engineering*, DiNenno P.J. Editor, Quincy, MA, USA, June 1995
4. Drysdale, Dougal, *An Introduction to Fire Dynamics*, Second Edition, John Wiley & Sons, University of Edinburgh, UK, 1998
5. The Chartered Institution of Building Services Engineers, *Fire engineering*, CIBSE Guide E, London, February 1997
6. National Fire Protection Association, *Guide for Smoke Management Systems in Malls, Atria and Large Areas*, NFPA 92B, 1995 Edition
7. Klote, J.H., Milke, J.A., *Design of Smoke Management Systems*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA, 1992
8. Fire Code Reform Centre, *Fire Safety in Shopping Centres*, Final Research Report Project 6, Australia, July 1998
9. Karlsson, B., Quintiere, J.G., *Enclosure Fire Dynamics*, CRC Press, 2000
10. Jackson, Lynn, *Modelling the future by computer*, Fire Prevention 215, December 1988
11. Chow, W.K., *Application of Fire Models*, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong
12. Rhodes, N., *Good for Design but Fundamentals Need More Research*, Mott MacDonald Group, Fire Surveyor, pp.5-10, 1990
13. Wickstr m, U, "TASEF-2, A Computer Program for Temperature Analysis of Structures Exposed to Fire", Lund Institute of Technology, Report No. 79-2, 1979.
14. Kevin B. McGrattan Glenn P. Forney, Fire Dynamics Simulator -User's Manual", Building and Fire Research Laboratory, NISTIR 6469, January 2000.
15. International Organization for Standardization ISO/TC/92/SC4, *Fire Safety Engineering – Assessment and verification of mathematical fire models*, Draft Technical Report 13387-3, Berlin, 1998

Paper 4

Using a Fire CFD Program, JASMINE, as a Fire Engineering Tool

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USING THE FIRE CFD PROGRAM, JASMINE,

AS A

FIRE ENGINEERING TOOL

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Introduction

The worldwide trend towards the adoption of performance based fire regulation has created a requirement for computer based fire simulation methods to be applied to "real" buildings and to include interactions between a fire and the internal (HVAC, ACMV) and external (wind) environments. Most available CFD fire simulation programs, such as JASMINE (Analysis of Smoke Movement IN Enclosures) were developed originally as research tools and applied to relatively simple scenarios (e.g. Steckler's single room experiment). Specialised fire engineering interfaces are required to accommodate complex problems efficiently and address the needs of the fire safety practitioners.

This paper discusses the importance of a specialised user interface targeted at fire safety practitioners for the application of CFD fire simulation tools for practical fire engineering problems (principally for smoke control). Examples include large buildings such as shopping centres, airport terminals and tunnels.

Simulation Models for Performance Based Design

A performance based design exploits a series of calculation methods to demonstrate that for a given set of conditions (such as fire location and heat release rate) the system under consideration will respond in such a way that a pre-specified safety criterion is achieved. For example, a smoke control system may be evaluated by calculating the depth and temperature of a hot gas layer at locations in a building and comparing the

time for unacceptable conditions to occur with the evacuation time for the occupants. Several methods can be used for performing such calculations. These may include:

- "Simple" Calculations such as the use of empirical expressions to estimate mass flow rate in a plume or flame height.

- Zone Models, for example, the BRE design guides or computer programs such as CFAST.

- Computational Fluid Dynamics (CFD) Models such as JASMINE, SOFIE, PHOENICS or CFX.

The appropriate method for a particular application depends on the complexity of the problem and the final precision required.

The "simple" calculations have usually been developed as part of a prescriptive method and implicitly include assumptions, such as a maximum compartment size, that will limit their use. Zone models are developed from a qualitative description of a scenario (classically a fire plume filling a hot gas layer at ceiling level, like an inverted bath tub) and use empirical correlations and conservation principles to calculate values for layer depth, temperature etc. These include similar assumptions to the "simple" methods (and may be a set of "simple" calculations solved simultaneously) and will have similar limitations. It is usually possible to sub divide buildings into areas that can be regarded as being independent of each other for the purpose of smoke control, the simple methods or zone models can then be applied to each area. Achieving this sub division may impose restrictions on the design that may conflict with the architect's concept of the building or its function. Airport terminals and railway stations are clear examples. For some parts of the building such as shop units or offices the "simple" methods or zone models will be appropriate. However in such a case there is a requirement for a very large area where people can move without restriction. Creating a number of smoke reservoirs at high level may be one solution, but this may conflict with other requirements such as environmental control or the appearance of the building.
CFD models are based on a first principles approach and are not restricted by the same limitations as the "simple" calculations and zone models . They offer the simulation of

smoke movement in large and/or complex spaces including the external environment (wind) and any interaction with air movement in the building due to environmental effects or air conditioning (HVAC, ACMV). This versatility may require long processing times and provides a large amount of data for interpretation. Furthermore the software can be difficult to use. Although based on "first-principles" (conservation of mass, energy etc), CFD models include some empirical sub-models for processes such as turbulence, combustion and heat transfer to surfaces. In addition the use of numerical methods to solve the descretised forms of the partial differential equations describing fluid flows introduces the potential for numerical errors.

The use of simulation models, such as CFD models, is only one component of a performance based design. The British Standard Draft for Development BS DD240: Fire Safety Engineering in Buildings [1] (Being reviewed and to be replaced by a new standard BS7974 [2]) describes a framework for performance based design outlined in figure 1. The Qualitative Design Review (QDR) would identify the need for a simulation, specify the scenario to be modelled and the relevant acceptance criteria. The simulations would then form a part of the Quantified Analysis and Assessment steps.

CFD Models and JASMINE

CFD models divide the volume to be simulated into a large number of small "control" volumes and solve conservation equations so that velocities entering and leaving the cell and scalar quantities (pressure, temperature, concentration etc) at the cell centre can be computed. These values are time varying in the case of transient simulations. The values in each cell are spatially averaged so it is critical that the cells are constructed so that the number of cells increased in regions where large changes in the flow with steep property gradients are expected (e.g. in the fire plume and at openings). This creates a large amount of data for each simulation which is usually presented using contour maps, iso-surfaces and arrows indicating velocity vectors. Presentations of weather forecasts provide familiar examples. A number of CFD software codes are currently available for solving fluid flow and heat transfer problems. Some are general-purpose codes and

others are specifically developed for a specific application, such as meteorology, or aerodynamics.

JASMINE (Analysis of Smoke Movement IN Enclosures) is a CFD code that has been developed for fire applications. A key component of this development has been a number of validation studies where the results of simulations have been compared to experimental measurements for scenarios ranging in size from small rooms to road tunnels [3,4,5]. These include a "blind" simulation (where the experimental results are not revealed until the simulation is completed) of a flashed over compartment fire [6].

Performing a CFD Simulation

Performing a CFD simulation is rarely (if ever) a matter of entering data, starting the computation, waiting for the results then analysing the data. Several preliminary simulations may be required to optimise the geometric detail and the numerical grid. Initial simulations may be needed to determine the environmental conditions that are present prior to the start of a fire. Finally the simulation may need to be conducted in a series of stages to examine individual components of the whole fire safety system. For example the effect of active systems, such as extract fans, can be included depending on the results of the simulation at a particular time. As part of a research study this tends to follow a cyclic or spiral cycle as shown in figure 2, which can be split into four steps:

- Setting up the problem, modifying the program if required
- Running the simulation
- Analysing the results
- Identifying changes to the problems setup or coding

These steps would need to be repeated until a solution to the problem has been found. On each cycle the understanding of the problem is increased.

A cyclic approach tends to be open ended and although it will educate the user and explore many options it will not reach a specific goal very quickly. An alternative approach is required for using a CFD model economically as a practical fire engineering tool.

Figure 3 shows an alternative approach based on a "water-fall" model that complements the broader methodology within a performance based method such as that described in DD240.

This begins with the Qualitative Design Review (QDR) which:

- establishes design objectives and acceptance criteria
- determines trial design(s)
- specifies fire scenarios

From this information the specification for a CFD simulation can be prepared. The specification includes:

- The extent and level of detail of the geometry to be modelled
- The location and heat release rate of the fire
- Pre fire environmental conditions
- Action of active fire systems

For a CFD simulation this provides sufficient information to design a numerical grid, select appropriate sub models (for combustion, thermal radiation etc) and run the program.

When the simulation is complete, checks need to be made to ensure that numerical convergence criteria have been met, extreme values of the calculated variables are physically realistic (minimum or maximum temperatures etc.) and that the solution is independent of the numerical grid (this requires repeating the simulation with a different grid). The flow patterns should also be inspected and any unexpected behavior explained.

When a "good" solution has been obtained the data specified by the QDR to determine acceptance of the trial design can be extracted. This may require further processing from the data provided by the CFD model. For example concentrations of fire products may need to be converted to visibility (OD) or fractional effective dose (FED) so that the comparison with the acceptance criteria can be made.

At each step of the procedure provision is made to return to the previous step if necessary, however the intention is to progress from one step to the next so that the simulation can be kept to a fixed time scale and budget.

JOSEFINE, a CFD interface for Fire Engineering

Interfaces for CFD programs are usually "inward looking" and directed at controlling the CFD solver rather than addressing the problem being solved. In the case of general purpose codes this is unavoidable due to the wide range of applications that can be addressed; however, facilities are usually provided so that a user can customise the names of variables and select relevant units.

Specialised CFD applications may adopt a "black-box" approach (figure 4) so that the user does not require any CFD expertise and is not given any control of the CFD solver. The success of the simulation relies on default values and options selected by the developer. Alternatively the interface may form a "wrapper" around the CFD code so that the user can use the system with the application terminology, but still has access to the CFD solver, as shown in figure 5.

BRE have developed a "wrapper" interface, JOSEFINE (JASMINE or SOFIE Fire Interface) that provides additional fire engineering tools for users of either JASMINE or SOFIE. JOSEFINE has five principle components:

- Fire Definition
- Geometric Model Builder
- Grid Generator
- JASMINE Simulation Control
- Results Analysis

In addition there is an online help feature and an integrated 3D viewer.

The rest of this paper will concentrate on the use of JASMINE with JOSEFINE.

Fire Definition

This component allows the user to specify the fire source used in JASMINE simulations. Like most fire simulation programs JASMINE does not attempt to predict the heat release rate (HRR) of a fire. The HRR data may be taken from experimental data, one of the NFPA t^2 fire growth curves or otherwise prescribed based on the anticipated fire hazard. In a performance based design the definition of the fire source is one of the tasks of the QDR. JOSEFINE allows the user to select a fuel and specify the maximum fire area and a transient of steady state heat release rate. This data can then be used to calculate Q*, a modified Froude number for the source, flame heights using an empirical correlation and total fuel consumed. These give the user an indication of the relevance of a particular fire specification to a particular application, for example a high value of Q* is typical of a jet flame, such as a gas leak, not a furniture fire.

Geometric Model Builder

The geometric model builder is a simple CAD style application that allows the user to build a representation of a building. JASMINE is limited to a single block Cartesian mesh. Consequently, sloped and curved features have to be approximated using a series of stepped blocks. Compared to the detail found on engineering drawings, only the significant geometric features of the building such as compartment walls and openings may be sufficient of most CFD simulations. The geometry builder also allows the user to locate mechanical extracts and supplies and to specify the thermal properties of materials. The 3D viewer allows the user to inspect the geometry as it is built in three dimensions.

Grid Generator

The grid generator allows the user to select the part of the geometry model required for the simulation. The boundary conditions at the edge of the calculation domain can be specified (this includes the definition of wind profiles) and a set of grid rules applied to construct the basic grid. The grid rules set grid lines at the edges of the geometric

objects and add additional cells near solid surfaces and in the fire source. Dividing large cells into a number of smaller cells then completes the grid. The user has facilities to override the grid rules and may manually edit the grid. The 3D Viewer allows the grid and geometry to be viewed together.

Solver Control

This allows the user to select sub models and adjust control parameters for the solution procedure (e.g. selecting file names, numbers of iterations, convergence limits etc.). The graphical display of monitor values and residual errors is provided for checking the numerical convergence of the solution.

Results Analysis

In addition to examining the results from a simulation as text file the 3D viewer can be used to view iso-surfaces, contours and vectors (e.g. figure 6). For transient simulations, iso-surfaces may be animated.

The JOSEFINE interface has allowed JASMINE to be used effectively and more reliably for fire safety engineering applications. In nine months some fifty fire engineers, with varying experience of using computer fire models, have attended training courses for JASMINE and were able to perform a simple simulations within a couple of hours. In the same period 10 complex simulations (involving between 50000 and 150000 cells) have been undertaken by BRE for large fire-safety consultancy projects.

Example

Simple geometries such as a single room that may be used for training or demonstration purposes do not exploit the full potential of the interface. A complex scenario represented by a large number of objects (blocks and walls) identifies requirements such are the need to "cut and paste" objects in the model builder and problems that can occur when visualising problems with large aspect ratios such as tunnels. Figure 6 is an internal view of an atrium space (30m by 30m by 14m high) in a public building. This has large open stairways on each side leading to galleries and offices at higher levels. The pyramid indicates the location of a 500kW fire. The right hand image shows an iso-surface (displayed as a wire-frame) of a 15°C temperature rise predicted by a JASMINE simulation. The geometry includes over 100 objects including some external features so that the characteristic features of the building can be recognised.

Future Developments

A performance based design may require a number of simulation tools for evaluating the overall fire safety strategy of a building. In order to develop an integrated modelling methodology JOSEFINE has the potential be used as an interface to CRISP (BRE's fire risk assessment model) to model occupant egress and THELMA to model the thermal response of the building structure. A common interface to several models ensures data consistency between simulations (e.g. each model uses the same geometric data) and provides a more efficient working environment.

References

1. 'The Application of Fire Safety Engeinnering Principles to Fire Safety in Buildings' Draft British Standard code of Practice, DD240, 1994.

2. Chartes D 'Engineering a Solution' Fire Engineers Journal, November 2000

3. Cox G, Kumar S and Markatos N C. 'Some Field Model Validation Studies' pp. 159-171 in Fire Safety Science, Proc of the First International Symposium, Hemisphere, 1986

4. Kumar S. 'Field model simulations of vehicle fires in a Channel Tunnel shuttle wagon', In Proc. 4th International Symposium on Fire Safety Science, Ottawa, Canada, 1994, p. 995

5. Kumar S, Heywood G M and Liew S K. 'JASMINE sprinkler model - Some validation studies', In Proc. 1st European Symposium on Fire Safety Science, Zurich, Switzerland, 1995, p. 79.

6. Miles S D, Kumar S and Cox G. 'Comparisons of 'blind predictions' of a CFD model with experimental data', Proc 6th International Symposium on Fire Safety Science, Poitiers, p543-554 (1999).

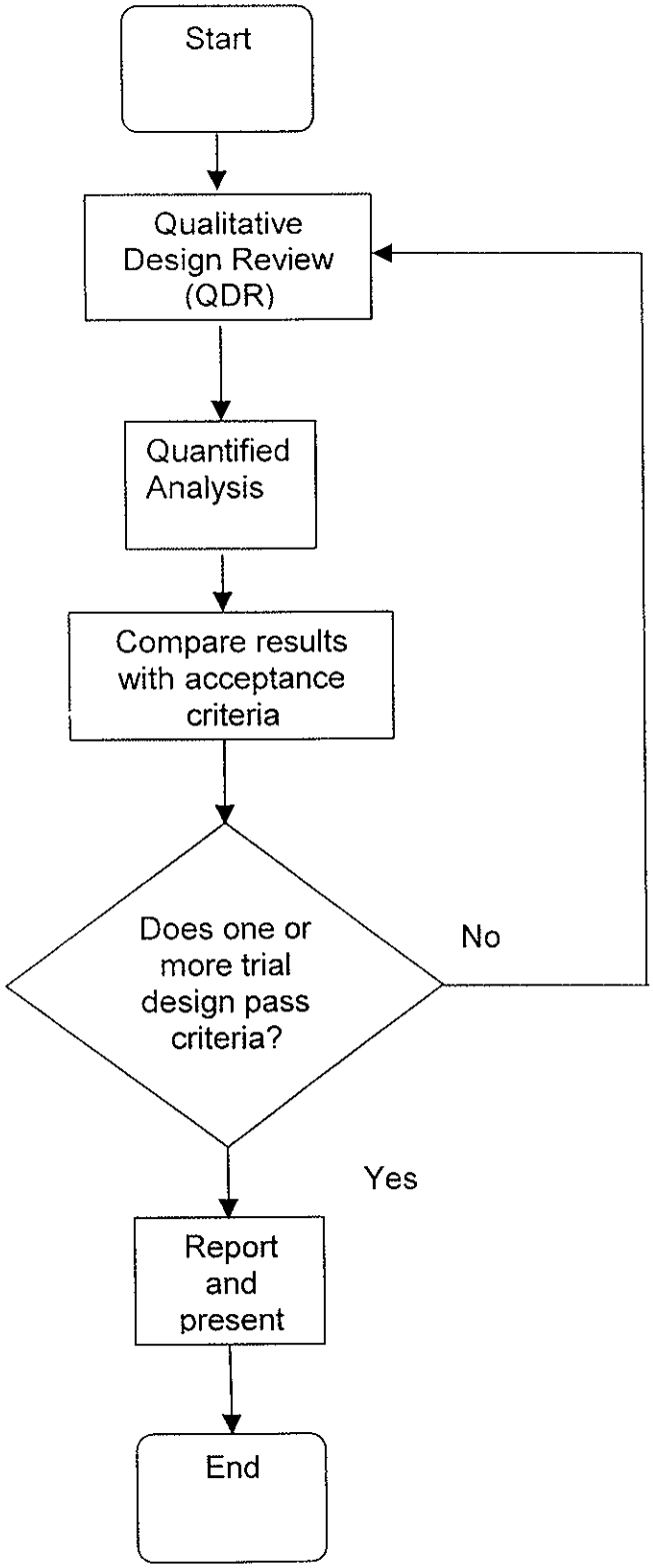


Figure 1 : DD240 Basic Design and Analysis Procedure

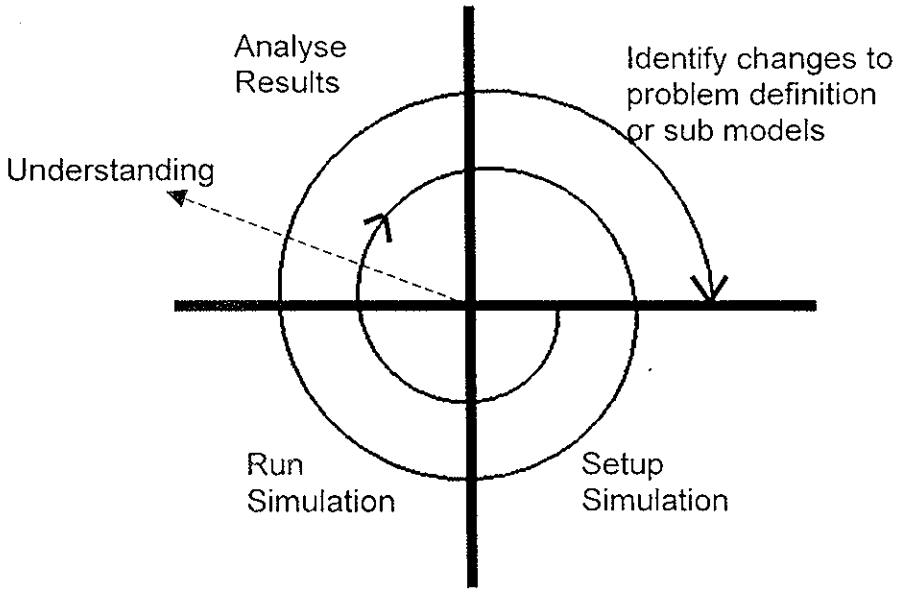


Figure 2 : Spiral Development model

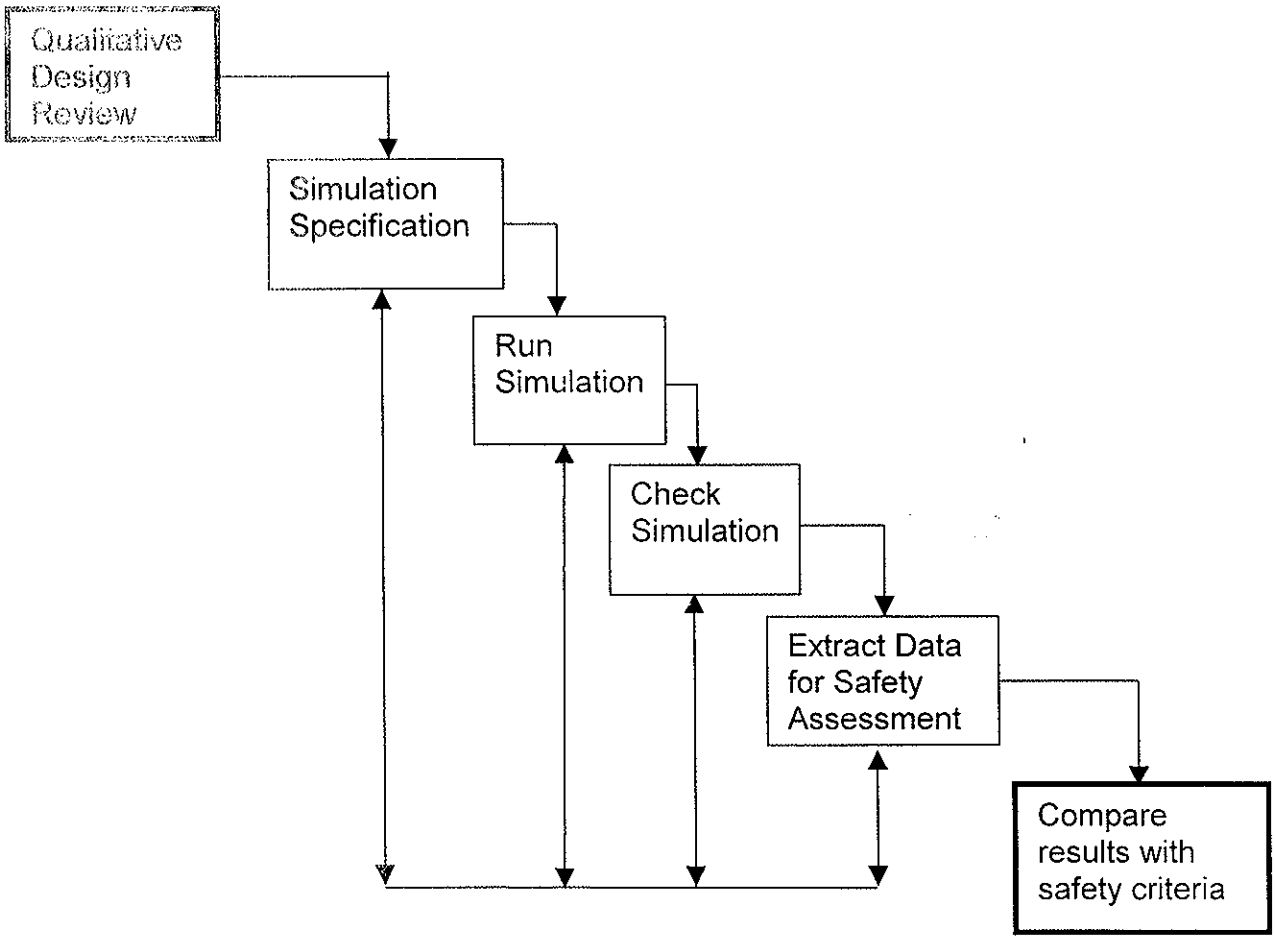


Figure 3 : "Waterfall model " including DD240 stages

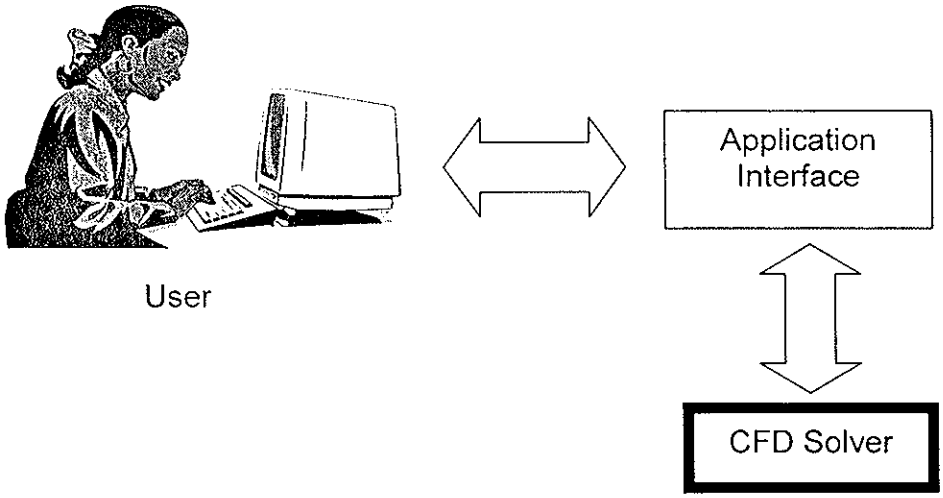


Figure 4 : "Black-Box" interface to CFD solver

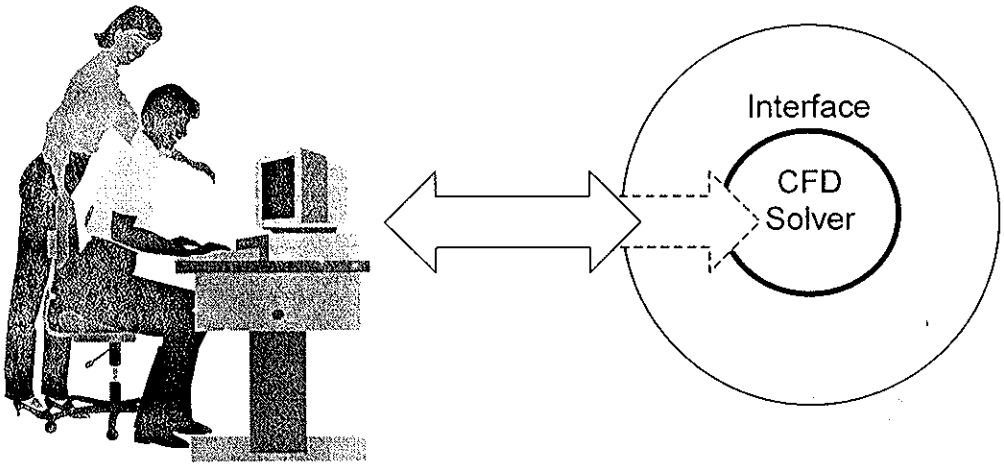


Figure 5 : "Wrapper" interface to CFD solver

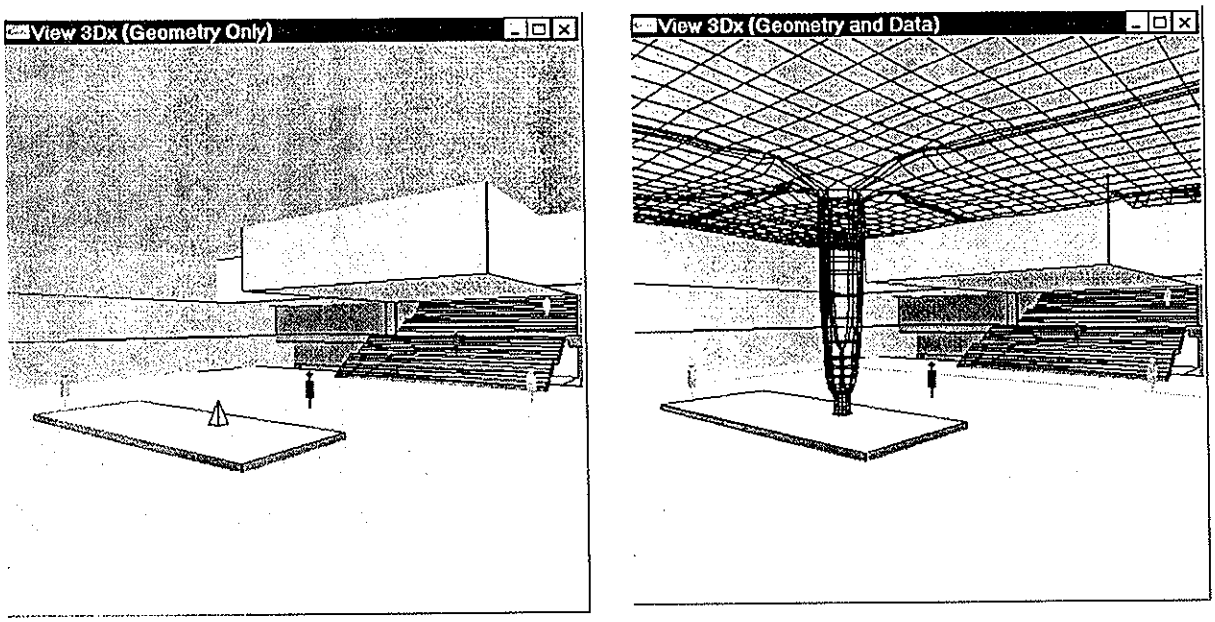


Figure 6 : JOSEFINE 3D viewer showing geometry and geometry with a mesh of a 15°C rise iso surface (figures are 1.67m tall)

Paper 5

Field Model :

Its Use in Analysing the Airwell Design

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Joint FSB/FETC Project Team

FIELD MODELLING –

ITS USE IN ANALYSING THE AIR-WELL DESIGN

CPT. LIM LAM KWANG
JOINT FSB/FETC PROJECT TEAM

INTRODUCTION

The Code of Practice for Fire Precautions in Buildings, 1997 permits the design of air-wells (Clause 2.2.13 (a)(iii)) with vertical openings of minimum width 6m and an area of not less than 93 m^2 (see **ANNEX A**). This is required for smoke and heat ventilation so that the approaches to exit staircases can be made smoke-free. This implies that ventilation of smoke and heat from the air-well would be deemed sufficient and applicable for any building height and configuration. The extent to which this assumption is valid has to be investigated.

Natural ventilation has been accepted as a reliable and cost effective method of ventilation since no maintenance or running costs are needed. The intensive use of land and space for development in Singapore means that using natural ventilation for emergency facilities such as exit staircases, exit passageways and smoke-stop lobbies will become a common feature of buildings in the future.

Collaboration was initiated between the Fire Safety Bureau (FSB) and Ngee Ann Polytechnic's Fire Engineering Technology Centre (FETC) to study the ventilation of smoke and heat from inside an air-well using the computational fluid dynamics (CFD) modelling program JASMINE. JASMINE was developed by the Fire Research Station (FRS). It is well validated and has been used as an investigating tool for an assortment of projects. A high performance workstation including a 3D graphical interface was used for generation and visualisation of the 3D flow patterns and temperature profiles of the

naturally ventilated air-well under different fire load situations. The results show that there is a direct relationship between the clear width and area of an air-well. It has been shown that the existing requirements (Clause 2.2.12(a)(iii)) for an air-well are only applicable for buildings of heights less than 9 m.

Employing computational fluid dynamics CFD tools such as JASMINE has been useful in achieving a higher level of confidence for fire safety design in buildings. It has also demonstrated the ease with which building professionals can make use of scientific means to achieve a higher level of fire safety in buildings.

OBJECTIVE

The objective of this study is to determine the minimum size of an air-well for different heights, clear widths and fire loads (1-5 MW), such that in the event of a fire, smoke and heat can be removed to a level of safety comparable to that of an external open space.

APPROACH TO STUDY

The approach to this study is shown in the following stages:

(a) Stage 1: Simplify the problem.

(b) Stage 2: Specify fire source and model configuration.

(c) Stage 3: Decide on grid mesh and modelling matrix.

(d) Stage 4: "Shadow" and validate the results.

Stage 1: Simplify the problem

Firstly, the problem is simplified [1] as the amount of details incorporated in a CFD model is critical to the computer processing time. This means that appropriate assumptions have to be made and details have to be evaluated so that the simulation results will not be affected.

(a) Structural details

Structural features such as corridors and staircases which are commonly found in air-wells were not modelled since the aim is to study the ventilation through the air-well.

(b) Stack Effect

Heat energy generated by humans, appliances and other activities is considered insignificant compared to the amount of air movement generated by the fire load (1 –5 MW). It is assumed that heating is evenly distributed throughout the entire building. Any source of process heat which generate large amounts of energy at a specific location should be considered separately.

(c) Natural Ventilation Openings (from occupied space or void deck)

In this study, only the vertical air-well is modelled. Other natural ventilation openings were not considered. This is to reduce the complexity of the model. The amount of natural ventilation openings to the air-well is difficult to assume for different times of the day.

(d) Weather effects

Effects of weather such as wind and rain will have a significant impact on the ventilation of the air-well. However, the frequency of their occurrence is to quantify

(e) Fire Load

The types of combustible materials present in a building vary. The fire load is also dependent on the distribution of the combustible materials and their intended usage. This is especially evident in industrial buildings where highly combustible and flammable materials are stored. To cater to the wide range of fire conditions, two fire loads of 1 MW and 5 MW are used in this study to simulate a small and a large fire.

(f) Building Construction

Building construction refers to the type of construction materials such as whether the walls and ceilings are made of materials like timber which promotes rapid combustion or non-combustible materials like cement black which has minimal effects. Thermally, the walls and floors of the building are assumed to be adiabatic.

(g) Fire Origin and Compartment

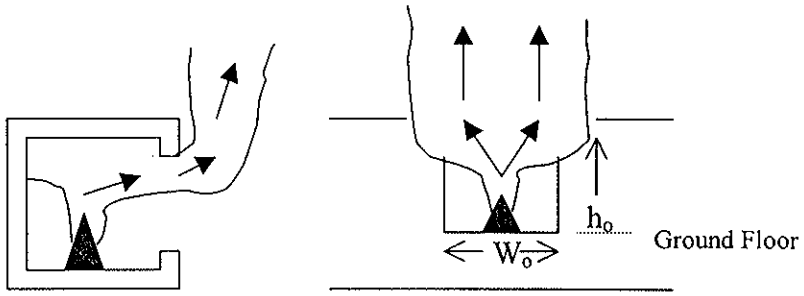
The fire can occur in any location of a building. But the worst case is when the fire originates from the lowest level of a building, as in this study. This means that the amount of air mixing between the combustion gases and the incoming outdoor air would be at the maximum. The fire compartment was modelled to a size of 10 m by 6 m.

(h) Flow Conditions

The condition of air flow in a fire is assumed to be fully turbulent. This involves activating the appropriate turbulent flow functions.

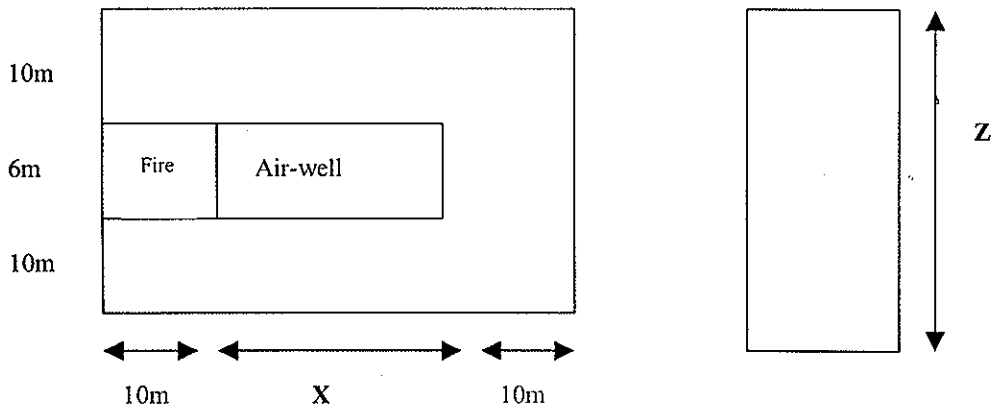
Stage 2 : Specify fire source and model configuration

A typical smoke plume produced by the fire source as it emerges into the air-well is shown below :



Section View **Front View**

W_o is the width of the opening to the air-well. It is assumed to be 6m to represent a shop unit. The position of the shop in the air-well is shown below. It is compartmented by two walls separating it from the rest of the floor.

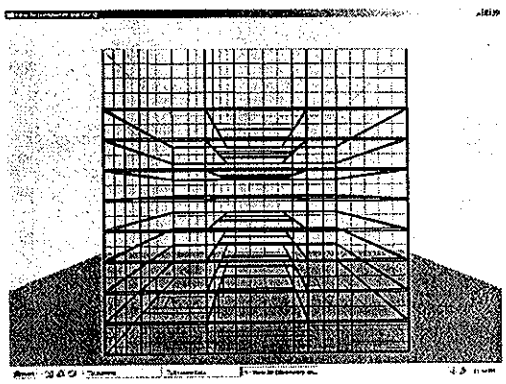


Plan View of Model **Elevation View of Model**

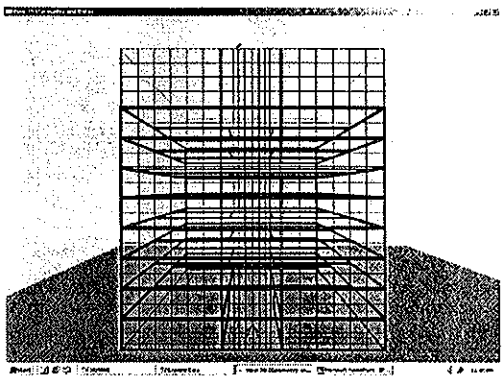
The model was simulated by varying building height (**Z**), fire size (1-5 MW) and the clear width (**X**) of the air-well.

Stage 3: Decide on grid mesh and modeling matrix

Grid lines are uniformly distributed for the building But a finer grid mesh was used for the fire source and the near-wall positions. The estimated number of cells used is in the range of 70,000 to 80,000.



Side View (varying) of grid lines for Air-well



Side View (fixed) of grid lines for Air-well

The domain above the air-well is extended to a distance of 6 m above the top of the building to account for the atmospheric boundary condition. This domain is maintained for all the simulations. The modelling matrix consists of three variables : height of building, clear width of air-well and fire load (1 MW and 5 MW). This is shown below.

X/Z	Clear Width (m)				
Height (m)	6	8	10	12	14
9	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW
18	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW
24	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW
36	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW
48	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW
60	1&5MW	1&5MW	1&5MW	1&5MW	1&5MW

Stage 4: "Shadow" and validate the results

Each simulation run was deemed to have converged if the :

(a) Number of sweeps > 1000

(b) Residual value < 0.1

X/Z	Clear Width (m)				
Height (m)	6	8	10	12	14
9	F1&5	P1&P5	P1&5	P1&5	P1&5
18	F1&5	P1&F5	P1&5	P1&5	P1&5
24	F1&5	P1&F5	F1&P5	P1&5	P1&5
36	F1&5	F1&5	P1&F5	P1&5	P1&5
48	F1&5	F1&5	F1&5	P1&5	P1&5
60	F1&5	F1&5	F1&5	F1&5	P1&5

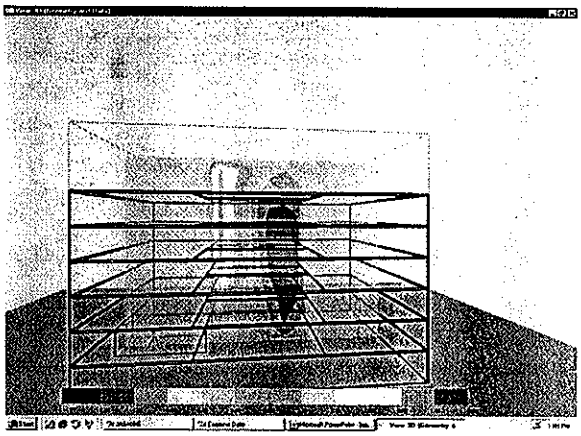
P = Pass condition,

F = Fail condition,

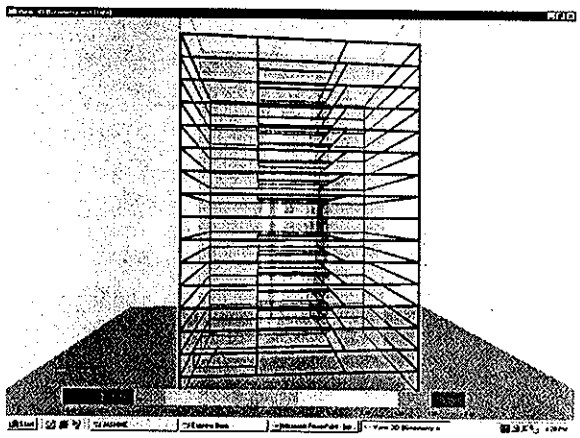
1 and 5 denote fire size of 1MW and 5MW respectively.

Each situation is adjudged to have 'pass' or 'fail' based on the smoke movement and a safe temperature profile as shown in the graphical output.

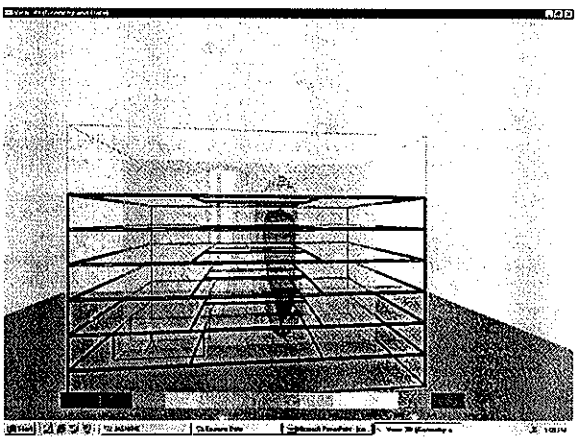
Examples of 'fail' situations :



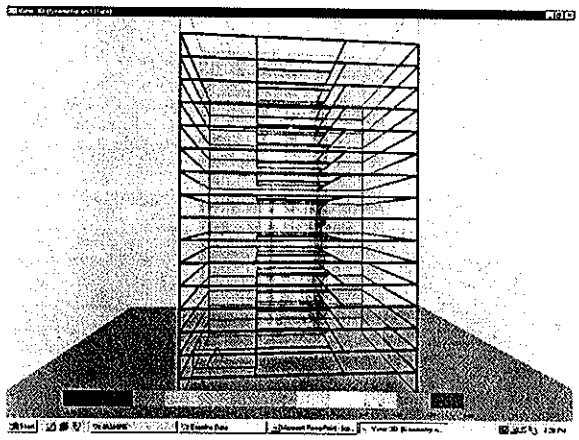
18m high, 6m long courtyard
Y - plane W contour (1MW)



48 m high, 10 m long courtyard
Y - plane W contour (1 MW)



18m high, 12m long courtyard
Y - plane W contour (1MW)



48m high, 12m long courtyard
Y - plane W contour (5MW)

Acceptable Conditions for Air-well

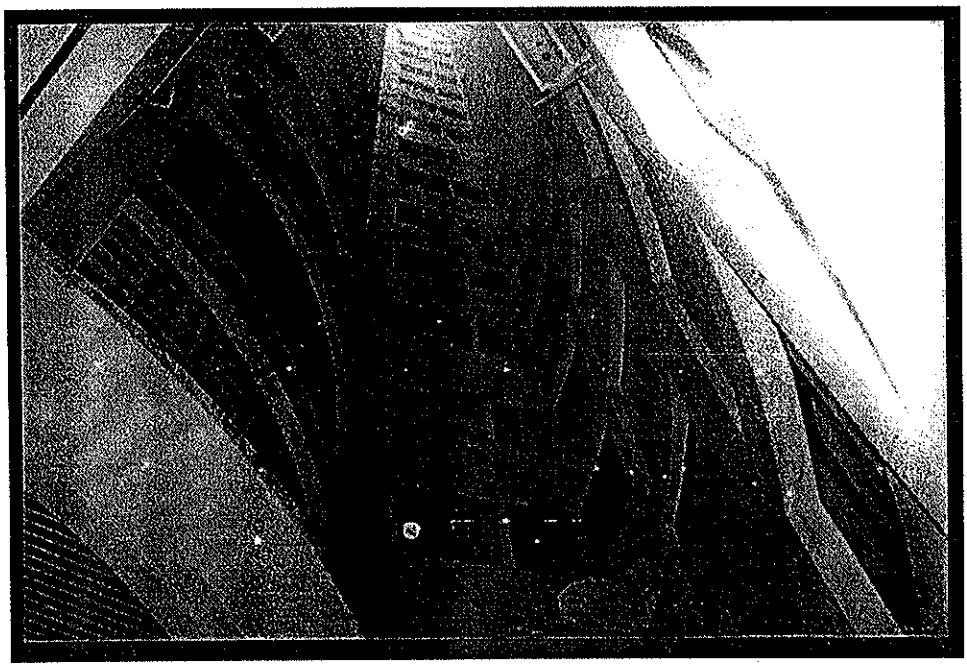
The following factors are used to determine the effectiveness of a smoke ventilation system :

(a) Exposure to toxic products of fire causing incapacitation or death
(b) Exposure to high temperatures causing burns and risk of hypothermia
(c) Level of visibility, preventing or delaying occupant escape

To better understand the involvement of the above parameters in a fire, site visits to existing buildings were conducted. A fire investigation case involving an external fire incident was also studied.

(a) Site Visits to Existing Buildings

The site visits were intended to provide an experience of what would be expected in an air-well. The air-well serves to provide lighting and ventilation to the building as shown in Photograph 1. Typical courtyard type of air-wells are commonly found in primary and secondary schools, conservation/old non-conservation shop-houses and industrial premises. This means that different fire loads according to their usage and building heights have to be included in the modelling.



PHOTOGRAPH 1 : EXAMPLE OF AN AIR-WELL USED FOR VENTILATION AND LIGHTING IN A 25-STOREY BUILDING

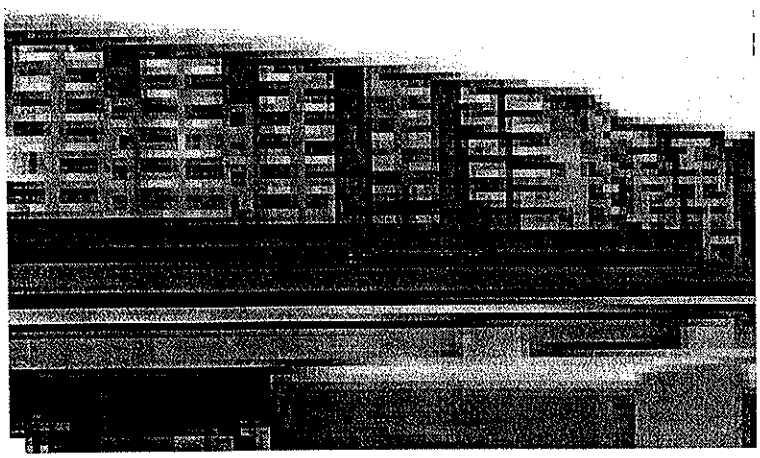
(b) Investigation of an External Building Fire

A search of past records revealed that the Geylang Serai Market fire was a case of an external fire incident. The fire happened near a block of HDB flats. The distance between the fire origin and the block of flats is 1.5 m. Due to the rapid growth rate, as plastic and paper materials were involved, there was considerable fire damage to both the block of flats and the market. The fire was estimated to have an intensity of between 1 MW to 3 MW at the peak of the fire.

The effects of smoke and heat on the block of flats was felt from the ground level up to the tenth level as shown in Photograph 2. It is likely that such an effect will be present in an air-well too. From the investigations conducted, it was observed that two conditions were critical for occupant escape :

(a) Air temperature inside air-well at 100°C
(b) Level of visibility (5-8 m)

Simulations were conducted for the transient state with the temperature set to the critical temperature. The results which were not acceptable are tabulated as shown.



PHOTOGRAPH 2 : FIRE DAMAGE TO A HDB BLOCK OF FLATS

Sensitivity Tests on the Model

Sensitivity tests were conducted according to the following :

(a) Changing the domain above the air-well from 6m to 12m.

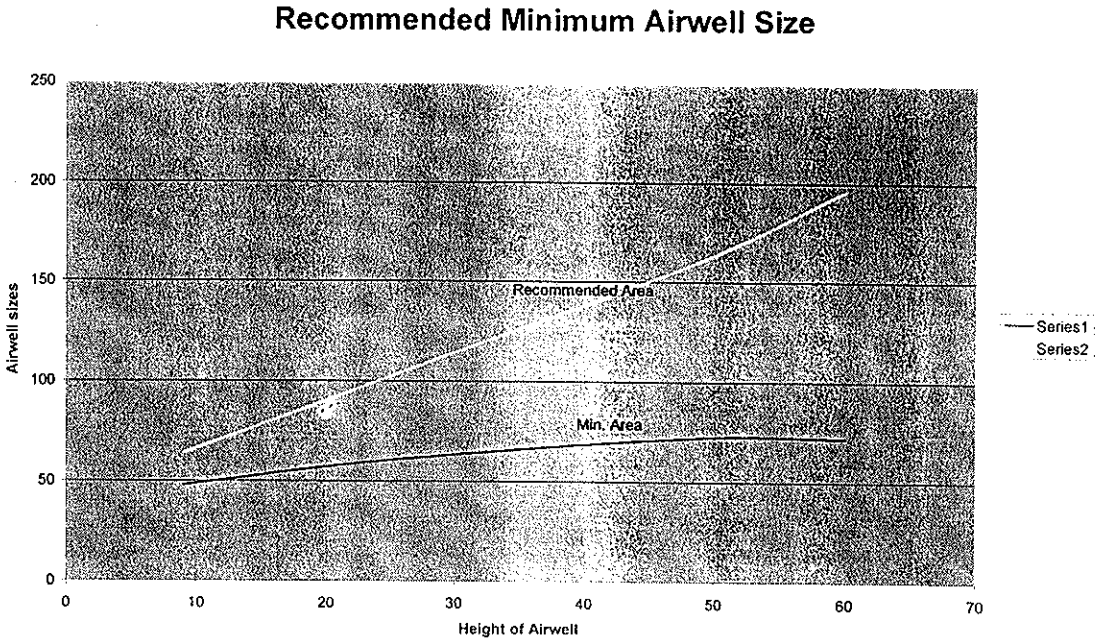
This is to determine whether the movement of smoke is restricted by the domain above the air-well. Selective tests have shown that the results are not dependent on the height of the domain.

(b) Doubling the number of grid line and cells

Increasing the number of grid line and cells will ensure that the results produced are not sensitive to the refinement of the grid mesh generated. In this study, the grid mesh over the fire source and the near-wall areas were doubled that of the surrounding areas.

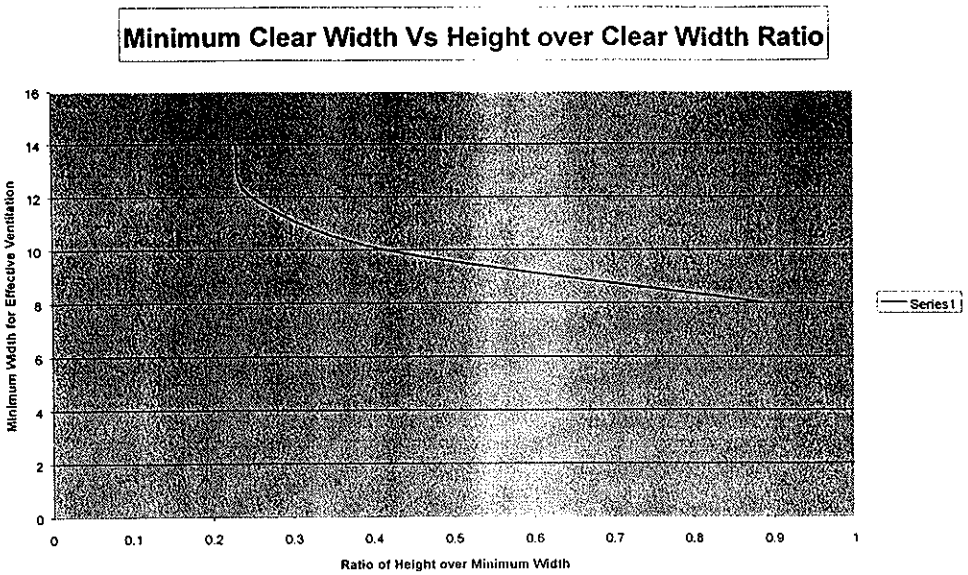
CONCLUSION

The results show that there is a direct relationship between the clear width in the air-well and the height of the building as illustrated in the graph below:



Height of Building (m)	Minimum Clear Width of Air-well (m)	Minimum Clear Area of Air-well (m^2)
9	8	64
18	10	87
24	10	103
36	12	134
48	12	165
60	14	196

Note: The recommended area is used after considering the possibility of fire occurring on different sides of the air-well.



Plotting the **Minimum clear width** against the **Ratio of height over clear width**, shows that there is a limit to the size of the opening as the curve straightens vertically at around the 0.2 ratio.

This study has served to demonstrate the effectiveness of the fire modelling tool. The findings made in this study have been forwarded to the Fire Code Review Committee for revamping the existing air-well requirements.

REFERENCES

1. Technical Memoranda TM 19:1995 "Relationships for smoke control calculation". CIBSE.

2. Code of Practice for Mechanical Ventilation and Air-conditioning in Buildings. CP 13:1980.

3. Code of Practice for Fire Precautions in Building 1997

4. BR 186 – Design principle for smoke ventilation in enclosed shopping centres

5. BR 258 – Design approaches for smoke control in atrium buildings

Paper 6

Development and Deployment

of

FiRECAM

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DEVELOPMENT AND DEPLOYMENT OF FiRECAM™*

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Many countries in the world, including Canada, are moving towards the more flexible performance-based building regulations and away from the present restrictive prescription-based regulations. Performance-based regulations allow the designers and building officials the freedom to come up with innovative designs that will provide a level of safety that satisfies the objectives established by the regulations. Such innovative designs often lead to lower fire protection costs. The implementation of performance-based building regulations can be facilitated by the development of engineering tools that can help assess the overall fire safety performance of a building.

Fire Models to Support the Introduction of Performance-Based Codes

To support the introduction of performance-based codes, many research organizations around the world are developing computer models that can help designers predict how fire and smoke develop in a compartment and spread to other compartments in a building [1]. These models include both field and zone models. The field models divide a compartment into many cells and compute, using computational fluid dynamics (CFD), the thermal and flow conditions in each cell. These models provide detailed information in a compartment but are computationally intensive and require a lot of computer time even with the fastest computers. An example of the field models is the JASMINE model that was developed by the Fire Research Station in the U.K. [2].

Different from the field models, the zone models divide a fire compartment into a number of characteristic zones, such as the upper hot layer, the lower cold layer, the fire plume and

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the compartment boundary. The conditions in each zone are modelled separately and then linked together through fluid dynamics and heat transfer equations. This approach simplifies the intensity of computation and allows previously developed models, such as plume models or ceiling jet models, to be applied. A notable model of this type is the CFAST model that was developed by the National Institute of Standards and Technology (NIST) in the U.S. [3].

Other more comprehensive models that predict not only the fire and smoke spread in a building, but also the expected risk to life of the occupants, are also being developed. These risk assessment models combine the interaction of fire growth, smoke spread, occupant response and evacuation, and fire department response to assess the expected risk to life of the occupants. Two such models that are being developed are the CESARE-RISK [4] that is being developed at the Victoria University of Technology in Australia and FiRECAM™ [5] at the National Research Council of Canada (NRC).

Development of FiRECAM™ and other Risk Assessment Models at NRC

To provide a tool that can assess the overall fire safety performance of a building, NRC is developing a computer fire risk-cost assessment model called FiRECAM™ (Fire Risk Evaluation and Cost Assessment Model). The model can assess both the expected risks to life of the occupants in a building, as well as the expected costs of fire protection and fire losses in the building. Therefore, the model can be used to identify cost-effective fire safety designs that provide a level of safety that is required by the code (performance-based code), or alternative designs that provide a level of safety that is equivalent to that of a code-compliant design (prescription-based code). The model is being developed in partnership with the Public Works and Government Services Canada (PWGSC) and the Department of National Defence Canada (DND).

To undertake the evaluation of fire risks and losses, FiRECAM™ simulates the ignition of a fire in various locations in a building, the development of the fire, smoke and fire spread, occupant response and evacuation, and fire department response. These calculations are performed by a number of submodels interacting with each other, as shown in Figure 1.

There are nine submodels that are run repeatedly in a loop to obtain the expected risk to life values and the expected fire losses from a set of probable fire scenarios that may occur in a building. The computer model also includes three optional submodels that can be run if the building fire characteristics and fire department response are not considered typical or if fire costs are required. One submodel is run only once to obtain the failure probability values of boundary elements. FiRECAM™ is the only comprehensive model in the world that includes the probability of fire spread in a building, the response of the fire department and the estimate of fire costs, in addition to the typical modelling of fire growth, smoke spread and human response and evacuation.

FiRECAM™ uses statistical data to predict the probability of occurrence of fire scenarios, such as the type of fire that may occur or the reliability of fire detectors. Mathematical models are used to predict the time-dependent development of fire scenarios, such as the development and spread of a fire and the evacuation of occupants in a building. The life hazard posed to the occupants by a fire scenario is calculated based on how quickly the fire develops and how quickly the occupants evacuate the building for that scenario. The life hazard calculated for a scenario multiplied by the probability of that scenario gives the risk to life from that scenario. The overall expected risk to life to the occupants is the cumulative sum of all risks from all probable fire scenarios that may occur in a building. Similarly, the overall expected fire cost is the sum of fire protection costs (both capital and maintenance) and the cumulative sum of all fire losses from all probable fire scenarios in a building.

Another research group at NRC, in partnership with the DND, is developing a new computer model to evaluate fire protection systems for light industrial buildings, with the primary focus on warehouses and aircraft hangers. FIERAsystem (FIre Evaluation and Risk Assessment system), is based on a framework that allows designers to establish objectives, select possible fire scenarios, and evaluate the impact of each scenario on life safety and property protection. The framework leads the user through a series of steps in setting up the problem, including defining building and occupant characteristics, and specifying fire safety objectives and appropriate performance criteria for fire and smoke

spread, occupant safety, property protection, continuity of operations, and environmental protection. Potential fire scenarios are then selected from a list, along with active and passive fire protection options to be evaluated.

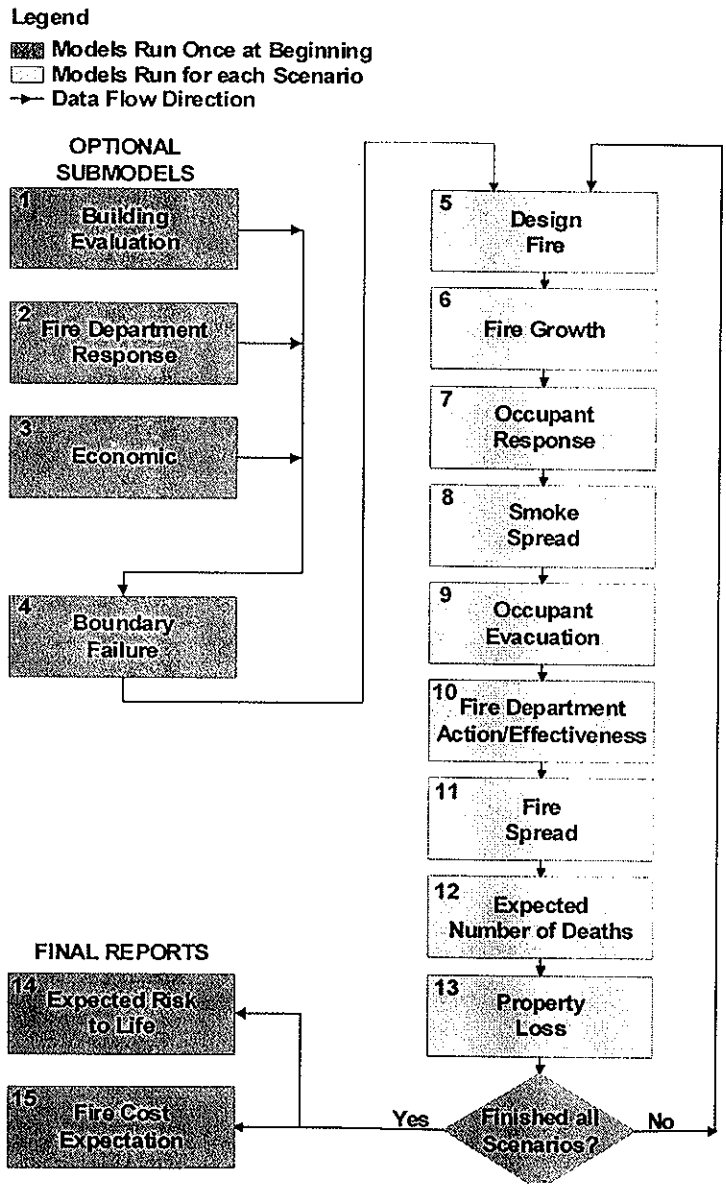


Figure 1 : FiRECAM flowchart

Deployment of FiRECAM™

Over the past decade, NRC, in partnership with PWGSC, has been developing a version of FiRECAM™ for PWGSC's use. The model, FiRECAM™ – Office Model, allows designers and regulators to evaluate the impact of various design options on life safety and property protection for office buildings. PWGSC owns most of the Canadian federal government buildings. The model will help PWGSC to identify cost-effective fire-safety designs for these buildings.

To help evaluate the performance of FiRECAM™ before its actual use, PWGSC has formed a number of task groups across Canada during the past three years. Groups were formed in Halifax, Montreal, Ottawa, Toronto, Winnipeg, Edmonton and Vancouver. Each task group consisted of PWGSC regional staff, fire consultants, building and fire department officials. Task group members were provided with the computer program as well as the necessary training, education and guidance. They learned how to apply the model as a fire safety assessment tool, interpret its results and understand its capabilities and limitations. The objectives of the evaluations were: a) to assess FiRECAM™ in order to determine whether its predictions were reasonable and realistic for applications to office buildings; and b) to provide constructive comments and recommendations for improving FiRECAM™ if there were any areas requiring improvement.

Real and fictitious case buildings were used in the exercise and numerous runs were conducted. For each building, a base fire safety design case was established and then one fire safety design parameter was changed at a time to determine the impact. In later runs, multiple parameters were changed to determine the impact of tradeoffs and additions. After each run, the members presented and discussed their results. At the end, they concluded that the predictions by the model in general were reasonable. In a few situations when the results differed from users' expectations, these differences were discussed and resolved. This is an important step in gaining the confidence of users and, ultimately, their acceptance and adoption of this program. Feedback gained from this comprehensive evaluation process also led to improvements in the computer program.

Following the evaluation of FiRECAM™ through PWGSC's task groups, NRC plans to release the FiRECAM™ - General Model by November 2001. The target date of November 2001 is set to allow sufficient time to fix bugs that may be identified through the current evaluation by PWGSC through March 2001. The executable module, the user's manual and the system model document will be available. Other reference material can be obtained from NRC Publications. NRC will not provide any technical support. However, training workshops may be provided at the request of the users and at full cost recovery. Users take full responsibility when they use FiRECAM™.

For those parties interested in developing the model further for their specific use, NRC could enter into a collaboration agreement that will allow the model to be further developed. For example, if Ngee Ann Polytechnic (NAP) wants to develop FiRECAM™ further for use in Singapore, a research collaboration could be setup between NAP and NRC. The collaboration will allow NAP to carry out the required research and development work, with the support by NRC researchers, to make FiRECAM™ applicable in Singapore. Such collaboration will benefit both organizations: allowing Singapore to have the use of FiRECAM™ and allowing NRC's FiRECAM™ to have a wider application. Currently, FiRECAM™ is being evaluated by Tianjin Fire Research Institute in China and the Australian Building Codes Board for such possible collaboration.

References

1. Friedman, R., "An International Survey of Computer Models for Fire and Smoke", J. of Fire Protection Engineering, Vol.4, No.3, 1992, pp.81-92.

2. Kumar, S., Cox, G., and Gupta, A. K., "Effects of Thermal Radiation on the Fluid Dynamics of Compartment Fires", Proceedings of the 3rd International Symposium on Fire Safety Science, Edinburgh, Scotland, July 8-12, 1991, pp.345-354.

3. Peacock, R. D., et al, "CFAST, the Consolidated Model of Fire Growth and Smoke Transport", Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, Maryland, February 1993.

4. Beck, V. R., "CESARE-RISK: A Tool for Performance-Based Fire Engineering Design", Proceedings of 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods", Maui, Hawaii, May 3-9, 1998, pp.319-330.

5. Yung, D., Hadjisophocleous, G. V., and Proulx, G., "A Description of the Probabilistic and Deterministic Modelling Used in FiRECAM™", International J. on Engineering Performance-Based Fire Codes, Vol.1, No.1, 1999, pp.18-26