CESARE-RISK: An Aid for Performance-Based Fire Design - Some Preliminary Results

VAUGHAN BECK and LONGDE ZHAO
Centre for Environmental Safety and Risk Engineering
Victoria University of Technology
PO Box 14428, MCMC,
Melbourne, Victoria, Australia, 8001

ABSTRACT

A risk assessment model termed CESARE-RISK is being developed. The model can be used to quantify the performance of a building fire safety design system in terms of two parameters; namely a risk to life safety parameter and an economic parameter. Accordingly, it is possible to identify alternative cost-effective fire safety system design solutions. Preliminary results have been obtained for a three-storey apartment building. The results were compared with fire statistics. It was found that in comparative terms, the model predictions agree well with statistical data, whereas in absolute terms the predicted results are higher.

Keywords: Risk Assessment, Fire Safety Design Solution, Fire Growth, Smoke Spread, Human Response and Evacuation

INTRODUCTION

In October 1996 the Australian Building Codes Board (ABCB) launched a new "performance-based" Building Code of Australia, (BCA, 96) [1]. This forms the basis of the first comprehensive set of performance-based building regulations in Australia.

To support the introduction of performance-based regulations, the Fire Code Reform Centre Limited (FCRC) was established as an independent organisation by a co-joint initiative between ABCB, industry and research organisations. Its mission is to develop for approval and adoption by the ABCB a cost-effective, engineered approach to fire safety design and to reform aspects of the existing building code based on similar principles.

In FCRC Project 4 a risk-assessment model (termed CESARE-Risk) is being further developed to quantify the performance of fire-safety systems designs in each occupancy category. Outputs from the project will specify alternative, cost-effective prescriptive solutions, suitable for inclusion in deemed-to-satisfy provisions of the BCA. This will provide additional flexibility to the BCA. In addition, the risk assessment model is expected to provide the basis for the development of the Fire Safety Design Manual in Project 5B. This latter project will include development of a systematic, fully performance-based, Fire Safety Design Code. The Code may become an Australian Standard, adopted by the BCA, to provide an acceptable methodology for identifying alternative solutions under the BCA, 96 whenever the prescriptive design approach is not adopted or is not appropriate. Project 5B includes also the development of a Commentary, Manual and "user-friendly" computer software (using CESARE-Risk as the computational component of the software) for each category of building occupancy. The Fire Safety Design Code will represent a further development of the FCRC Fire Engineering Guidelines document [2].

CESARE-RISK MODEL

CESARE-Risk is a risk assessment model that is used to quantify the performance of a building fire safety system. The model adopts a comparative cost-effective decision criterion described previously [3]. This criterion states that for an alternative design to be considered acceptable, the calculated Expected Risk-to-Life and Fire-Cost Expectation shall be equal to or less than the values for the same parameters for an equivalent design conforming to the deem-to-satisfy requirements in the regulations [4].

The CESARE-Risk Model is an expected value model that can be characterised by several distinguishing features; these are described below:

- Multiple scenarios are defined using an event tree. Each scenario has a probability of occurrence.
- Attached to each scenario is a time-dependent deterministic realisation obtained from a Fire Growth and Smoke Spread Model. Multiple realisations are separately attached to each scenario.
- Attached to each deterministic realisation for fire growth and spread are Human Behaviour, Fire Brigade and Staff Rescue Models. These response models are used to represent the actions of such groups in response to a single time-dependent fire growth and smoke spread realisation. These models are time-dependent, non-stationary stochastic response processes models. Accordingly, the output from these models are expected responses.
- Attached to deterministic realisations for severe fire growth are Barrier Response Models. These models are used to predict both the time and probability of failure of barriers. These predictions are developed from Monte Carlo simulations.
- To represent those cases where a fire has not been controlled by various extinguishment means, a non-time dependent, stochastic Fire Spread Model [3] is invoked. This model is used to predict the probability of fire spread from one enclosure to any remote enclosure. The Fire Spread Model uses the probability of barrier failure obtained from the Barrier Response Model.

Some of the constituent parts of the CESARE-Risk Model are described subsequently together with preliminary results that are applicable to multi-unit residential buildings.

Event Tree and Expected Value Model

The approach adopted in the CESARE-Risk Model is based on the recognition that the modeling of fire growth and spread in a building and its interaction with building components and human behaviour can be split into two components. The first component of the modeling consists of setting up an event tree to describe the conditions of building components. This is a static event tree describing such things as whether or not sprinklers (if there are any) are operational and effective. The event tree described elsewhere [5], is such that each path in the event tree represents a fire scenario that can run into several hundreds to thousands, each occurring with a probability. Listed in Table 1 are various building components and their assumed event conditions; probabilities of existence are attached to each of the event conditions. Additional factors included on an event tree (and not shown in Table 1) are: fire type (smouldering, flaming and flaming potential flashover fire) and the location of the fire (kitchen, bedroom or lounge).

TABLE 1: BUILDING COMPONENTS AND ASSOCIATED EVENT CONDITION

Building Component	Event Conditions (Probabilities Attached)		Representation of Failure (Spread) Condition
Window: Room of Fire Origin	Open	Closed	Temperature Criteria
Door: Room of Fire Origin	Open	Closed	Time and Probability
Door: Apartment of Fire Origin	Open	Closed	Time and Probability
Doors: Other Apartments	Open	Closed	Effective Door Open Area is Defined
Doors: Stairwell	Open	Closed	Effective Door Open Area is Defined
Sprinkler: If Installed	Effective	Not Effective	
Stair Pressurisation	Effective	Not Effective	
Smoke Management	Effective	Not Effective	
Alarms	Reliable	Not Reliable	
Barriers	Failed	Not Failed	Time and Probability
External Spread via Windows	No Spread	Spread	Time and Probability

Given the occurrence of a particular scenario, the real difficulty lies with the second component, namely in the modelling of both the fire environment and occupant and fire brigade responses to that environment. They consist of time-dependent, non-stationary stochastic processes of fire growth and spread and human behaviour, each of which have an infinite number of different realisations. Under such circumstances, the average or expected outcome over all realisations corresponding to the particular scenario can be estimated. Having repeated this procedure with each of the scenarios defined by the event tree, the global expected outcome can then be calculated by summing over the various scenarios, using the appropriate probabilities from the event tree.

The most satisfactory way of calculating an expected outcome for each scenario is an exact analytic one. There are some extremely simple situations where this is actually feasible [6]. However, in most realistic fire situations, recourse must be had to approximate methods. The next best approach appears to be Monte Carlo simulation. However, the Monte Carlo method itself can be extremely computationally intensive. One possible compromise is the recognition that the average outcome (for example, loss of life) over all realisations for a particular scenario, can be based on a limited number of representative realisations. Recourse could be made to a worst case condition; however, this is clearly inappropriate for an expected value model.

A method has been developed [7] such that the first four moments of the parent distribution can be replicated using a three-point realisation representation, where each realisation is specified by its time of occurrence and its proportion of occurrence. A simulation study was undertaken [8] to compare the expected number of deaths when untenable conditions set in during an evacuation with (I) the number obtained by taking just one average realisation and (II) the average number of deaths obtained from just three appropriately chosen realisations for each of the key random variables. The results of analyses (I) and (II) were compared with a Monte Carlo simulation for the same problem. Overall it was found that the three-realisation approximation drastically reduced the error associated with the single realisation to manageable proportions. Accordingly, it was decided to adopt the approximate three-realisation representation model as the basis for calculating expected risk-to-life values in the CESARE-Risk model, where the statistical parameters of the relevant random variables are determined a priori.

Modelling Considerations

Ultimately CESARE-Risk may be used as a design tool by consulting engineers and building approval officials to assist to identify cost-effective design solutions for buildings via FCRC Project 5B. As such, it is essential that the computer program execution time is commensurate with the expectation of designers; namely that the execution time is limited to hours not days. As a consequence of this restriction, there is a need to resolve the conflict between the desire for improved accuracy of estimates obtained from each of the sub-models (comprising the CESARE-Risk Model), recognising the uncertainties attached to each of the sub-models, and the time required to execute the risk assessment model [9].

Fire Growth and Smoke Spread Models

Computer modelling of fire development, smoke and fire spread are major components in risk assessment models. Zone models have the ability to reduce computational complexity of fire growth and smoke spread modelling without unduly sacrificing accuracy. This makes the zone model a powerful tool for risk-cost assessment. Following an evaluation of various fire growth models for possible inclusion within the CESARE-RISK Model, it was decided to select the NRCC Fire Growth Model [10], based on its merits of simplicity, efficiency and robustness. Predictions from the one zone NRCC Fire Growth Model have been compared with experimental results obtained for various fire conditions; namely, smouldering, flaming and flashover. Modifications to the NRCC Model have been undertaken to achieve closer agreement between the predicted and the measured results. This has led to the development of the NRCC-VUT Fire Growth Model [11]. In this model the combustion chemistry and gas flow calculations have been adjusted. Additional features, such as a variable flame spread rate, radiation enhancement by soot, fire spread to non-contiguous items and to wall linings and the effects of mechanical ventilation, have been incorporated. The results obtained in the validation program have demonstrated the robustness of the Model to predict the fire growth and the average room (exhaust) conditions from the enclosure of fire origin for smouldering, flaming and flashover fire types under different ventilation conditions.

The CESARE-SMOKE Model, which uses the zone concept and network approach to model smoke spread in large residential buildings, was developed at the Centre [12]. This model uses a two-zone approach to treat smoke movement on the level of fire origin. For smoke spread in a stairwell and on levels above the level of fire origin, the model uses a network approach. This model is capable of revealing both spatial and temporal variations in temperature, toxic species concentrations and smoke density in multi-storey buildings.

The predictions obtained from the model for smoke spread in a tower agreed reasonably well with experimental results [13]. The model is also being validated against recent experimental data obtained in the Experimental Building-Fire Facility at VUT. The CESARE-SMOKE Model is coupled with the NRCC-VUT Fire Growth Model to predict smoke movement to each enclosure in a building. In addition, times of crucial events, such as smoke detector and sprinkler activation, attainment of untenable and flashover conditions are over predicted with the integrated fire growth and smoke spread model.

To develop distributions for the time to untenable conditions for each of the three fire types (smouldering, flaming only and flaming, potential flashover fires) and from which three-point realisations are developed, 4000 simulations were conducted using the Fire Growth Model for defined scenarios [14]. These simulations were conducted by allowing variations in variables such as fire load density, room geometric dimensions and fuel properties. Given in Table 2 are the statistical properties of the resultant distributions for the time to untenable conditions for the three fire types relevant to the following ventilation conditions: room of fire origin door open, window closed and air handling off.

TABLE 2: STATISTICAL PROPERTIES FOR THE TIME TO UNTENABLE CONDITIONS FOR THREE FIRE TYPES FROM MONTE CARLO SIMULATIONS

Fire Type	Mean Time (min)	Standard Deviation (min)	Coefficient of Variation
Flashover	7.5	5.4	0.71
Flaming	6.5	3.4	0.53
Smouldering	71	33	0.46

Using the three-point realisation technique [7], it is then possible to define three representative realisations for the time to untenable conditions for each fire type given in Table 2.

Human Behaviour Model

The aim of the CESARE-Human Behaviour Model is to estimate the expected number of persons in different locations in an apartment building at different times during a fire incident. The Model consists of the Response Sub-model that deals with behaviour up to the time when evacuation begins by occupants leaving an apartment and the Evacuation Sub-model that deals with the movement of people in a building. The Human Behaviour Model, in conjunction with the Fire Growth and Smoke Spread Models, is used to estimate the cumulative time-dependent exposure of occupants to toxic and thermal effects. Based on these estimates occupants are defined to be in one of the following states: fatality, incapacitation, free to move or trapped.

Response Sub-model: The Response Sub-model deals with the behaviour of occupants up to the time when evacuation begins; namely, when occupants attempt to leave their apartments and enter the corridor. The Response Sub-model uses probabilities to define various outcomes and it includes response duration to allow for the recognition and coping stages of occupant behaviour during a fire. The structure of this sub-model is based on a review of the literature and the responses obtained by CESARE researchers to both detailed interviews and questionnaires from people who have experienced fires in their apartment buildings [15]. The response options for occupants of the apartment of fire origin are assumed to be either evacuate or remain and reflect the dominance of fire and automatic cues. Whereas, the possible response options for occupants of apartments of non-fire origin to cues (smoke, alarm or warnings from others) are assumed to be either evacuate, investigate (seek supportive information from the corridors before deciding to evacuate) or remain in the apartment. Information collected during the interviews was used to develop input data for the model. In addition, research is being conducted to estimate the probabilities and times of responses of sleeping subjects to alarms [16] and to estimate the duration required for awaking subjects to reach a stage where their responses will be similar to a fully awake person's responses. Given in Figure 1 is the Response Sub-model for apartments of non-fire origin.

Evacuation Sub-model. This is a dynamic network model that is used to estimate the spatial distribution of the expected number of occupants as a function of time. It is assumed that once occupants leave an apartment they seek to exit the building. However, this movement strategy can be altered by smoke conditions that can force occupants to seek alternative exit routes. If these exits are not available, then occupants are assumed to attempt to return to their apartment.

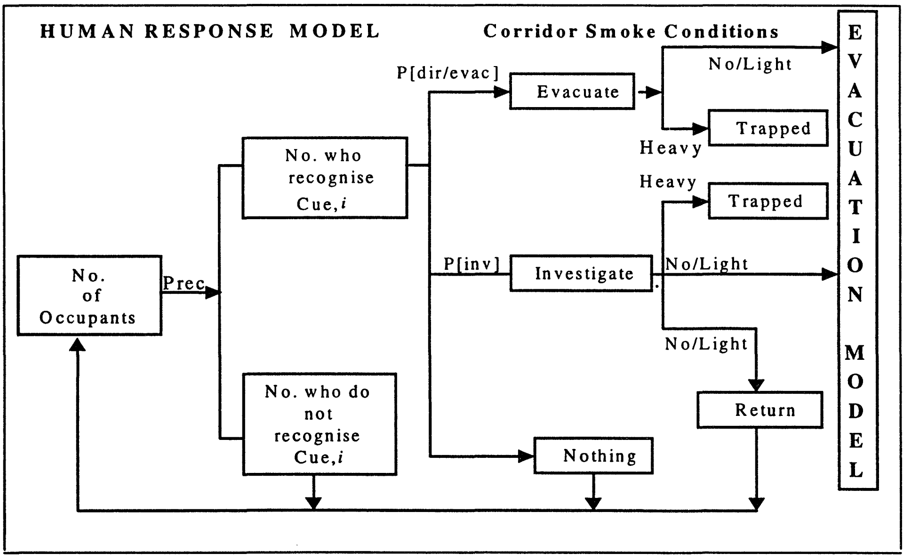

Figure 1. CESARE Human Response Model

Occupant Groupings. Since occupants can have different response parameters (probabilities, response duration and movement speeds), it was decided to define several occupant group categories. Census data was used to undertake a demographic analysis of the Australian population. This was used to provide an initial categorisation of the occupants. In recognition of the importance of the effect of age, drugs and alcohol and mobility-related handicaps on fire fatalities, further occupant groups were defined. A total of six occupant groups are identified.

Incapacitation and Fatalities. The calculation of occupant incapacitation and fatality is based on the temporal accumulation of toxic and thermal effects associated with each occupant (group). For simplicity, it is assumed that the effects of toxic gases and heat are mutually exclusive; that is, death can be caused by either toxic gases or heat, but not both.

Given in Table 3 are the response times and the associated probability pairs for the three realisation representation of the distribution of direct evacuation response time that was derived from data deduced from interviews with people who experienced a fire in their apartment building [15].

TABLE 3: THREE REALISATION REPRESENTATION OF THE DURATION TO START DIRECT EVACUATION (FROM THE TIME OF CUE RECOGNITION)

Occupant Condition	Time of Occurrence (sec)	Probability of Occurrence
Awake: Short Realisation	11.7	0.22
Medium Realisation	62.0	0.59
Long Realisation	121.3	0.19
Asleep: Short Realisation	46.2	0.46
Medium Realisation	267.0	0.39
Long Realisation	962.8	0.15

Fire Brigade Model and Staff Model

To quantify the effects of fire brigades, the Australasian Fire Authorities Council (the peak body representing fire brigades in Australia and New Zealand) has developed a Fire Brigade Intervention Model (FBIM). The FBIM has been adapted for use in the FCRC program [17]. The FBIM, which can be characterised as an event tree, is used to estimate the distribution for the time of arrival of the fire brigade at the enclosure of fire origin, as a function of the time of notification and the response times and operational procedures, resource availability and capability. In addition, actions such as fire control and extinguishment and search and rescue are also modelled deterministically as a function of the fire conditions, the number and distribution of occupants trapped and incapacitated and fire brigade operational procedures, resource availability and capability. Given in Table 4 are the pairs of arrival times and associated probabilities for the three-realisation representation of the distribution of the fire brigade arrival and setup at ground level prior to entering the building [18]. This applies to an automatic alarm transmission to a brigade situated in the outer suburbs of a major city and located 0.5 km from the fire incident.

TABLE 4: THREE REALISATION REPRESENTATION
FOR THE TIME AT WHICH FIRE BRIGADE COMPLETED ARRIVAL AND SET-UP

	Time (min)	Probability of Occurrence
Short Realisation	8.9	0.19
Medium Realisation	10.5	0.61
Long Realisation	15.4	0.20

Based on the FBIM, a Staff Rescue Model has been developed. This model retains the essential features of the FBIM and is used to estimate the number of occupants rescued as a function of staff intervention. While staff can respond earlier than the fire brigade, their rescue capability is restricted by both their numbers and their ability to operate in low-severity fire environments only.

Barrier Failure Models

To estimate the time-dependent performance of barriers under real fire conditions, a CESARE-Fire Barrier Model was developed [19] to predict the time and probability of failure of a range of timber-framed assemblies. In addition, separate deterministic failure models were developed for various steel, concrete and masonry barriers and structural elements [20]. These deterministic, time-dependent sub-models for fire severity, thermo-structural response and failure criteria were used to predict the time of failure of a barrier subject to a realistic fire and load combination scenario applicable to an apartment of fire origin. In the Centre, Monte Carlo simulations were undertaken to determine, for each numerical experiment conducted, whether failure of the barrier occurred and if so, the time of failure. This information was then used to estimate the cumulative probability density function of the time to failure. The Barrier Failure Models are used to provide input to CESARE-Risk; namely, the expected time of barrier failure and the overall probability of failure. Given in Table 5 are the mean times to failure and the overall probabilities of failure for certain barriers and structural elements having various Fire Resistance Levels when exposed to realistic flashover fire and loading conditions; consideration is given to the variability for fire severity and thermo-mechanical properties.

TABLE 5: TIME AND PROBABILITY OF FAILURE FOR SELECTED STRUCTURAL MEMBERS

Element type	Fire Resistance Level (min)	Probability of Failure (%)	Average Time of Failure, (min)
Steel Stud Wall	60	4.39	57.3
Steel Stud Wall	90	1.62	69.3
Steel Stud Wall	120	0.15	101.6
Concrete Wall	60	3.23	59.9
Concrete Wall	90	0.29	94.7
Concrete Wall	120	0.04	130.4

Economic Model

The Economic Model is used to estimate the Fire-cost Expectation parameter; this is one of two performance parameters that are used in the decision-making process to identify cost-effective fire safety system design solutions for buildings. The Economic Model has been previously described [21]. The model includes the following components:

- Cost of investment for providing active and passive fire protection features in the building
- Cost of maintenance and inspection associated with active protection features
- Expected monetary loss due to the loss of contents and costs associated with the repair of the building.

As part of the development for the CESARE-Risk Model, additional features have been added to the Economic Model [22]; namely:

- Damage to contents caused by smoke
- Repair cost to the building fabric from damage caused by smoke
- Damage to both contents and the building caused by water from either sprinkler operation or fire brigade activities.

RESULTS AND DISCUSSIONS

To illustrate the application of CESARE-Risk, preliminary results are presented here for the expected risk to occupants in a three-storey apartment building in which alarms are fitted in all apartments and no sprinklers are installed. The predicted results for the various fire scenarios are tabulated in Table 6.

TABLE 6: PRELIMINARY RESULTS FOR A THREE-STOREY BUILDING WITH APARTMENT ALARMS

Occupant Condition	Apartment of Fire Origin Door	Stair Door	Expected Fatalities per 1000 Fires		
			Smouldering	Flaming	Flashover
Awake	Open	Open	0.0	52.8	110.2
Awake	Open	Closed	0.0	5.6	110.6
Awake	Closed	Open	0.0	0.0	0.0
Awake	Closed	Closed	0.0	0.0	0.0
Asleep	Open	Open	0.0	68.8	482.2
Asleep	Open	Closed	0.0	48.2	300.5
Asleep	Closed	Open	0.0	15.3	173.1
Asleep	Closed	Closed	0.0	15.3	173.1

The results presented in Table 6 indicate the following:

- Apartment of Fire Origin (AFO) door (open/closed) condition has a significant effect on the fatality rate
- If AFO door is closed, the condition of stair door has little effect on the fatality rate
- If AFO door is open, the condition of stair door makes little difference if occupants are awake, but has a significant impact if occupants are asleep
- Occupant asleep condition has a significant impact on the fatality rate
- Smouldering fires have effectively zero risk in all cases
- Flaming fires have a high risk potential if occupants are asleep and the AFO door is open
- Flashover fires are the major contributor to risk

According to Australian statistics [23], the number of fires initiated in kitchen, bedroom and lounge rooms in apartment buildings, between 1989 - 1993, are given in Table 7.

TABLE 7: AUSTRALIAN FIRE STATISTICS — LOCATIONS OF FIRE INITIATION

	All Residential Buildings		Apartment Buildings	
Location	No. of Fires	Proportion	No. of Fires	Proportion
Kitchen	13,862	57%	2,287	64%
Bedroom	5,851	24%	778	22%
Lounge	4,667	19%	506	14%

From the same statistical database, the proportions of three types of fires are given in Table 8. In this analysis it was assumed that fires that undergo a transition from smouldering fires to flaming fires are classified as flaming fires, and fires that undergo a transition from smouldering to flaming and reached flashover conditions are classified as flashover fires. Also from fire statistics, approximately 70% of the kitchen fires occurred when occupants are awake, and 50% of the bedroom fires and lounge fires occurred when occupants are awake. The proportions of fire types and their distributions are used as inputs to the model.

The predictions given by the CESARE-Risk are summarised in Tables 9 to 10. In this case the probability of apartment door open is assumed to be 1%, and the probability for the stair door open is assumed to be 10%. The predicted results, in terms of the proportions of fatalities, due to kitchen fires, bedroom and lounge fires, are compared with fire statistics in Table 9. As can be seen the predictions are in good agreement with the fire statistics.

TABLE 8: PROPORTION OF THREE FIRE TYPES

Location	Smouldering	Flaming	Flashover
Kitchen	37%	60%	3%
Bedroom	14%	70%	16%
Lounge	16%	71%	13%

TABLE 9: PROPORTIONS OF FATALITIES

	Prediction (%)	Statistics (%)
Kitchen Fires	32	26
Bedroom Fires	42	47
Lounge Fires	26	27

Predicted results were compared with fire statistics for fatalities per 1000 fires for different building designs; the comparison is summarised in Table 10. As can be seen from the table, for the building design with no alarms and no sprinklers, the predicted number of fatalities per 1000 fires is approximately 21. The results for alarms and sprinklers are based on the reliability of alarms of 0.86 and sprinklers 0.985. Both values were obtained from fire statistics. The effectiveness of the sprinkler was assumed to be 0.95 which implies an efficacy of 0.965. Values in the range of 0.95 to 0.98 are commonly used for sprinkler effectiveness among Australian fire protection engineers. The lower value was used for this exercise. Using these reliability and effectiveness values, the fatalities per 1000 fires for buildings with corridor alarms only, apartment alarms only and sprinklers only are 21, 11 and 10 fatalities per 1000 fires respectively. Thus, there is effectively no difference between buildings with no alarms and no sprinklers and buildings with corridor alarms only, and there are significant reductions in risks for the other two cases. The fatality rate for buildings having apartment alarms was found to be significantly lower. This was also the case for buildings fitted with sprinklers only. The reductions for these two design cases are approximately 47% and 53% respectively.

TABLE 10: COMPARISON WITH FIRE STATISTICS:
FATALITIES PER 1000 FIRES FOR DIFFERENT BUILDING DESIGNS

	MODEL PREDICTION				ACTUAL
	No Alarms and No Sprinklers	Building Corridor Alarms Only	Apartment Alarms Only	Sprinklers Only	Fire Statistics
Kitchen Fires	8.5	8.6	5.1	4.5	4.4
Bedroom Fires	46.1	45.8	23.1	20.7	16.7
Lounge Fires	39.6	39.4	20.3	18.2	15.8
Overall (Weighted Average)	21.1	21.1	11.2	10.0	8.7

The results given in the final row of Table 10 are the weighted average values; where the probabilities of 64%, 22%, 14% for kitchen fires, bedroom fires and lounge fires respectively were used. Accordingly, the weighted average value for the statistical data is 8.7 fatalities per

1000 fires whereas there are some 7 fatalities per 1000 fires for all fires in all locations because bedroom fires and lounge fires are more hazardous. Given that during the time period (1989 to 1993), some 9% of the all fires occurred in buildings with alarms and some 10% of the all fires occurred in buildings with sprinklers, it can deduced that the model prediction of the overall fatality rate is approximately 18 fatalities per 1000 fires (kitchen, bedroom and lounge fires with the proportions given by the statistics). This is roughly twice as high as the comparable statistical value.

CONCLUSIONS

In reality, fire and the human responses to fire can have many different scenarios. Indeed fire and the responses to fire are inherently time-dependent, non-stationary stochastic growth and response processes. Risk-cost assessment models use a rational and systematic methodology to evaluate and integrate the multiplicity of possible outcomes from the effects of fire in a population of buildings having the same design features. The CESARE-Risk Model is an advanced example of such a risk-cost assessment model. It is based on the use of multiple fire scenarios, where the inherent stochastic nature of fire and response to fire are considered and where deterministic models are used to predict the time-dependent variation of the fire environment throughout a building. The model is based also on the use of multiple realisations per scenario. Presented in this paper are some input data that has been developed for the CESARE-Risk Model together with some preliminary results obtained from a risk assessment investigation. The predicted overall fatality rate by the model is approximately twice as high compared with fire statistics; however in relative terms, the predictions are in good agreement with statistics. This gives confidence in the adoption of a comparative cost-effective decision making criteria. The improvement of model predictions, in absolute terms, is one of the current research topics of the Centre.

ACKNOWLEDGMENTS

The authors acknowledge the significant contribution to the development of the CESARE-Risk Model from their colleagues at the Centre for Environmental Safety and Risk Engineering; namely, Ms P Brennan, Emeritus Prof. M Hasofer, Dr Y He, Dr. A. Sanabria and and Mr. D. Verghese. The authors acknowledge also the financial support provided by the Fire Code Reform Centre Ltd and Australian Research Council Collaborative Grants.

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