3. Weidmann, Ulrich, „Transporttechnik der Fußgänger", *Schriftenreihe des IVT 90*, ETH Zürich, 1992.
4. Yamori, K., "Going with the flow: Micro-macro dynamics in the macrobehavioral patterns of pedestrian crowds", *Psychological Review 105(3)*, 530-557, 2001.
5. IMO, "Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships", IMO, MSC/Circ. 1033, 2002.
6. AlGadhi, S., H. Mahmassani, and R. Herman, "A speed concentration relation for bi-directional crowd movements with strong interaction", In: 7.
7. Schreckenberg, M. and S.D. Sharma, "Pedestrian and Evacuation Dynamics", Springer, Berlin, 2002.
8. Burstedde, C., K. Klauck, A. Schadschneider, and J. Zittartz, „Simulation of pedestrian dynamics using a 2-dimensional cellular automaton", *Physica A 295*, 507—525, 2001.
9. Fruin, J., "Pedestrian Planning and Design", New York, Metropolitan Association of Urban Designers and Environmental Planners, 1971.
10. Galea, E., "A general approach to validating evacuation models with an application to EXODUS", *Journal of Fire Sciences 16(6)*, 414—436, 1998.
11. Gershenfeld, N., "The Nature of Mathematical Modelling", Cambridge, Cambridge University Press, 1999.
12. Hamacher, H. and S. Tjandra, "Mathematical modelling of evacuation problems – a state of the art", In: 7.
13. Helbing D., "Traffic and related self-driven many particle systems", *Rev. Mod. Phys. 73(4)*, 1067—1141, 2001.
14. Henderson, L., "The statistics of crowd fluids", *Nature 229*, 381—383, 1971.
15. Kirchner, A., H. Klüpfel, A. Schadschneider, and M. Schreckenberg, "Simulation of competitive egress behaviour", *accepted for publication by Physica A*, 2003.
16. Klüpfel, H., T. Meyer-König, J. Wahle, and M. Schreckenberg, "Microscopic simulation of evacuation processes on passenger ships", In *Proc. Fourth Int. Conf. On Cellular Automata for Research and Industry"*, pp. 63—71, London, Springer, 2000.
17. Pauls, J., "Movement of People", Chapter 3-13, pp. 3-263—3-285, In: DiNenno, P. (Ed.), "SFPE Handbook of Fire Protection Engineering", (2nd ed.), National Fire Protection Association, 1995.
18. TraffGo GmbH, "PedGo Users' Manual", Duisburg, 2002.
19. Transportation Research Board, "Highway Capacity Manual", Washington D.C., TRB, 1994.
20. Weckman, H., S. Lehtimäki, and S. Männikö, „Evacuation of a theatre: Exercise vs. calculations", *Fire and Materials 23(6)*, 357—361, 1999.

THE USE OF EVACUATION SIMULATION, FIRE SIMULATION AND EXPERIMENTAL FIRE DATA IN FORENSIC FIRE ANALYSIS

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ABSTRACT

This paper examines the application of evacuation and fire modelling tools to forensically analyse a fire scenario ***similar*** to the tragic Gothenburg fire incident of 1998. It is not claimed that the analysis accurately reproduces the Gothenburg incident, as a key component required for such a forensic analysis, i.e. the evolution of the fire is not adequately represented within the evacuation model. However, the model predictions bare a striking resemblance to the events that took place during the actual incident. The model predictions correctly show that the evacuees experienced severe congestion during their attempted evacuation. While over predicting the number of fatalities, the model successfully predicted the fatality order of magnitude. Furthermore, the predicted location of the fatalities matched that found in the actual incident. In addition, the number of injuries predicted in this scenario matched those produced during the actual incident. The analysis provides insight into the tragic event and an understanding of why so many people died at the Gothenburg incident. Clearly, evacuation and fire simulation models have an important role to play in fire investigation.

INTRODUCTION

The ability of Computational Fire Engineering (CFE) tools such as fire and evacuation models to simulate realistic incidents is important for engineering design applications as it provides a further means to validate these tools. However, a growing area of interest is the use of CFE tools for forensic fire analysis and incident investigation. In this paper, fire data - generated from small-scale experiments and fire simulation - reflecting an actual incident is used in conjunction with the buildingEXODUS evacuation model in an attempt to forensically analyse and better understand the outcome of an actual incident. Given that the outcome of the incident is known, comparisons can be made indicating which factors were likely to exert a strong influence on the outcome of the incident. When attempting to simulate an actual incident, great care must be taken to ensure that the initial and boundary conditions are represented as accurately as possible. However, the process involved in incorporating fire data is complex and subject to many assumptions. In most cases it is extremely difficult to accurately represent these controlling conditions as they unfolded during the actual incident. The precise nature of these conditions are simply not know to the extent that is necessary to allow an accurate computer based reproduction of the actual incident. Thus when using models for forensic analysis it is essential that simulation results are viewed as being indicative rather than absolute. In many cases, computer simulation can be used to rule out possibilities.

The case selected for analysis in this paper is the Gothenburg Disco incident of 1998[1]. Information concerning this incident was gathered from several sources, primarily the fire investigation incident report from National Fire Protection Association (NFPA)[1], the Swedish National Testing and Research Institute (SP) experimental report[2] and a number of relevant reports by Fire Alarm Central and other fire safety departments, as well as several website articles on the subject[3-12]. Fire hazard data used in the analysis was based on the 1/4 scale fire experiment conducted by SP as part of their analysis of the incident. This data could not be used directly in the evacuation analysis due to the reduced scale of the experiments and because many of the fire specific data required by the evacuation analysis was not collected. In reality, the fire hazard data eventually utilised by the buildingEXODUS forensic analysis may not closely replicate the original incident due to numerous approximations that needed to be performed to convert the data into a useful format. It should be emphasised that given the process involved in manipulating the fire hazard data that it is only possible for us to assert that we are modelling a *Gothenburg type* incident, rather than claiming to represent the actual event. However, this does allow us to identify the type issues associated with this incident and more generally in attempting to perform forensic analysis. This enables the model to be used to examine the hypotheses suggested in the NFPA incident report as well examining other aspects of the incident.

THE GOTHENBURG INCIDENT

On the evening of October 29 1998, a fire developed in the premises of the Macedonian Association in Gothenburg Sweden. On the evening of the fire, some estimates of the number of people in the disco go as high as 400 people. The building was approved by the local authorities for an occupancy of 150. Witnesses confirm that the dance hall was very crowded, according to some witness reports people were standing shoulder-to-shoulder and unable to dance[1].

The fire started in a stairwell adjacent to the disco hall. The disco was on the upper floor of an old industrial two-story building, served by two stairwells at each end of the structure (see Figure 1). There were two exits, one located at each end of the hall, each equipped with a single door that swung outward in the direction of travel and led to stairways. The main stairway on the northwest end discharged directly to the exterior. The other stairway on the southeast end discharged into a corridor on the ground floor, which then led to the same external exit.

The stairwell located in the southeastern end of the building was used to store approximately 40 chairs on the middle landing. The fire originated in this area amongst the chairs. Shortly before midnight - some time after the fire was started - the door leading to the southeast stairwell was opened, allowing smoke from the fire to

enter the main area of the building. It is unknown if the door was closed again after the fire was detected. This stairway effectively became impassable and was not available during the evacuation. The only viable means of egress from the disco was through a single exit, which was soon overloaded by the number of people simultaneously attempting to evacuate. Given the limited means of exit, a few people managed to escape through the windows. From some of the windows it was possible to jump down onto the roof of a lower building, while others were forced to jump from windows – located 2.2 m above the floor - which led directly to the street level, some 6 m below.

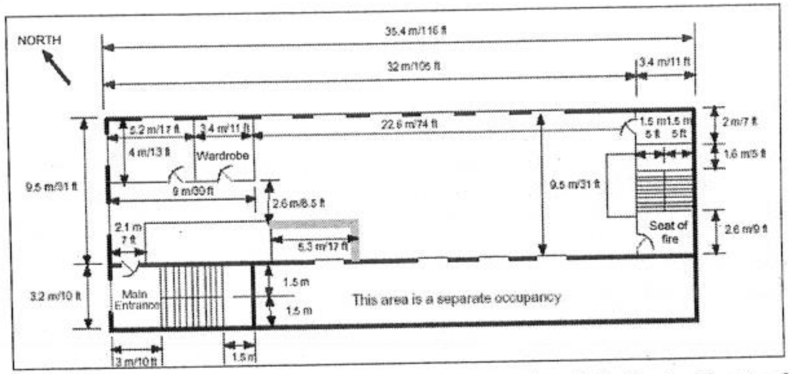


Figure 1: Floor plan of Gothenburg Disco building in which the incident took place[1]

In this incident 63 people died, of which 43 were found 'piled' around the internal exit leading to the main stairwell. Fire fighters reported that their access to the hall was blocked by a wall of bodies inside the doorway that reached the top of the doorjamb[1]. Other victims were found in a side room known as the 'Wardrobe', off of the Disco room, where they had apparently sought refuge. In addition 180 people were injured.

The NFPA concluded that the level of overcrowding, the lack of a fire alarm system and the ignition of combustible storage material in the stairwell contributed to the large loss of life in this incident[1].

REPRESENTATION OF THE FIRE IN THE EVACUATION ANALYSIS

The fire hazard data used in this paper is based on the small-scale fire experiments (1/4) conducted by SP as part of the official investigation[2]. It should be noted that these experiments were not performed with the intent of utilising them in detailed evacuation analyses but to understand the fire dynamics. The data is therefore not ideal for evacuation analysis. An important difference between the experiments and the actual incident is the fire fuel. In the experiments, the fire was simply represented using wood cribs. Thus the toxic gas species produced and their concentrations in the experimental fire are unlikely to represent those generated in the actual fire incident. This is an important omission as toxic gases such as CO and HCN were the likely main cause of death in the majority of cases during the original incident. Furthermore, the experimental investigation studied a range of ventilation openings and fire locations so as to derive a better understanding of the possible fire dynamics. In this analysis, we use the results from only one of the 14 fire scenarios studies. During the experiments, the mass loss rate of the wood cribs was measured as was the temperatures, gas concentrations and optical density at several locations throughout the structure. However, these measurements relate to the ¼ scale fire tests. Clearly, this data could not be used directly within the full-scale evacuation analysis and so a procedure was developed to scale up the data.

The evacuation analysis made use of the following fire hazard data: temperature levels, radiative heat flux, toxic gas levels (CO and CO_2 only), O_2 concentrations and smoke optical density. The basis of this data was generated from the small-scale fire experiments. However, to make use of this data in the evacuation analysis the data had to be scaled to represent a full-size incident. Several methods were used to achieve this.

The toxic gas, smoke concentrations and O_2 levels were obtained directly from the small-scale experiments using both temporal and spatial scaling factors[13]. Once again it must be emphasised that the gas concentration representation is a gross approximation due both to inaccuracies in the original experimental representation (i.e. using the wood crib rather than the actual fuel) and the scaling approach adopted. Temperature and radiative heat flux levels were determined using the CFAST zone model[14]. CFAST was used to simulate the ¼ fire experiments. When a parameter set was determined that accurately reproduced the small-scale experiments these were applied to the full-scale geometry in order to determine appropriate temperature and heat flux levels. Further details concerning the scaling approach can be obtained in another publication [2,15].

It must be emphasised here that the small scale experimental data used in this analysis is at best a crude approximation to the actual fire and furthermore, the scaling and fire modelling analysis undertaken to make this data appropriate for the full-scale analysis add greater uncertainty to the accuracy of the predicted fire atmosphere.

THE buildingEXODUS EVACUATION MODEL

buildingEXODUS is an evacuation modelling package developed by the Fire Safety Engineering Group at the University of Greenwich and designed to simulate the evacuation of large numbers of people from complex structures[16-20]. The model comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models. The software is rule-based, with the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. Architectural plans can be loaded straight in to the simulation suite to represent the

structure or the user may avail themselves of a number of interactive design tools. On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model.

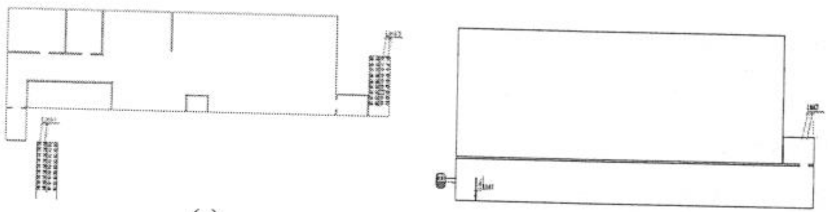
The Toxicity submodel determines the physiological impact of the environment upon the occupant. To determine the effect of the fire hazards on occupants, buildingEXODUS uses an FED toxicity model[21,22]. FED models assume that the effects of certain fire hazards are related to the *dose* received rather than the exposure *concentration*. Within buildingEXODUS, as the FED approaches unity the occupant's mobility, agility, and travel rates can be reduced making it more difficult for the affected occupant to escape. The buildingEXODUS toxicity model considers the toxic and physical hazards associated with elevated temperature, thermal radiation, HCN, CO, CO_2 and low O_2 and estimates the time to incapacitation. When occupants move through a smoke filled environment their travel speed is reduced according to the experimental data of Jin[23,24].

The thermal and toxic environment is determined by the Hazard submodel. This distributes hazards throughout the environment as a function of time and location. buildingEXODUS does not predict these hazards but can accept experimental data or numerical data from other models. The fire hazards are specified at two arbitrary heights that are intended to represent a nominal head height and crawling height. When occupants are considered to be erect, they are exposed to the hazards at head height (irrespective of their actual height) and when the occupants elect to crawl, they are exposed to the hazards at the crawl height. Simulations produced by buildingEXODUS can be replayed in three-dimensional virtual reality using the vrEXODUS software.

In this paper several terms are used to describe the results produced by buildingEXODUS. These include: *TET* (Total Evacuation Time, essentially the time for the last person to evacuate), *PET* (Personal Evacuation Time, evacuation time associated with an individual), *CWT* (Cumulative Wait Time, the amount of time spent by an individual in congestion during the evacuation), *Distance* (the distance travelled by a person during an evacuation), *FIH* (an individuals cumulative exposure to radiative and convective heat), *FIN* (an individuals cumulative exposure to narcotic gases), FIH_c (an individuals cumulative exposure to convective heat) and FIH_r (an individuals cumulative exposure to radiative heat).

EVACUATION MODELLING ASSUMPTIONS

In this section we detail the key assumptions and model parameters used in the evacuation analysis. Due to space constraints only a single scenario is presented here. This was only one of a much larger set of scenarios performed, the results of which are presented elsewhere[15]. For the scenario presented here, 10 repeat simulations were performed using the same population. The starting point for the evacuation analysis is taken as the time when the door to the fire stair is first opened, allowing the fire hazards to enter the disco hall. In the scenario examined, the geometry layout used adhered as closely as possible to the dimensions of the actual structure derived from the floor plans provided (compare Figure 2 with Figure 1). The external exit was attributed with a unit flow rate of 1.33 occ/m/s. Note, this is the maximum flow rate that the exit is allowed to attain however; it does not mean that the exit will necessarily operate at this rate.



(a) (b)

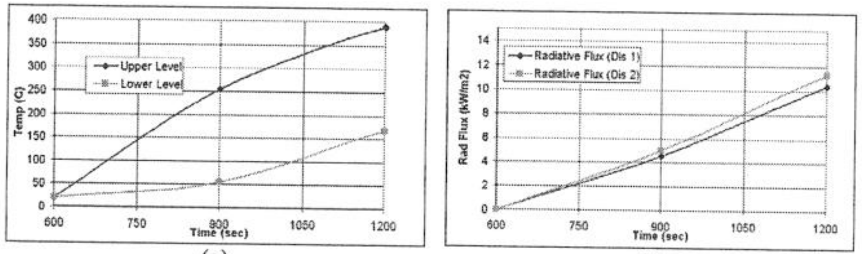
Figure 2: Geometric layout of the building as used in buildingEXODUS showing (a) first floor and (b) ground floor

The geometry was populated with 400 people who were distributed throughout the 'DISCO' room on the second floor. The population was generated from a standard buildingEXODUS population distribution with attributes varying as shown in Table 1. As shown in the table, we assume that the occupants have an instant response time i.e. they react immediately at the start of the incident (when the hazard enters the room).

Table 1:Basic characteristics of simulated population

Attribute	Specification
Age	17- 29 Years
Gender	Male-Female
Response Time	Instant response
Mobility	1.0
Fast Walk	1.2 - 1.5 metres/second
Walk	90% * fast walk
Crawl	20% * fast walk

The fire hazard data described in section 3 was imported into the buildingEXODUS model. This data relates to the Smoke levels, the temperature, the radiative flux, the CO level, the CO_2 level and the O_2 level for the main Disco room. All hazards were determined at two heights (head height and knee height). Within the evacuation analysis, the disco hall was treated as a single zone for the temperature and smoke concentration distribution, two zones for the radiative flux distribution, and three zones for the toxic gas distribution.



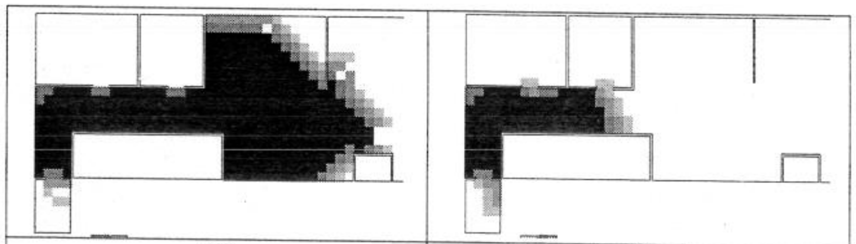
(a) (b)

Figure 3:(a) Calculated (a) temperature and (b) radiative flux levels (at two locations in the Disco room) used in the buildingEXODUS analysis.

The fire hazard data is assumed to impinge on the evacuation analysis some 600 seconds after fire initiation (see Figure 3). This event corresponds to the opening of the door to the fire stair. In the FED model relating to heat, the incapacitation level criteria was used rather than the pain criteria (i.e. evacuees are assumed to succumb once they are deemed to be incapacitated). In addition, the relevant behavioral options were selected to enable the people to crawl when the environmental conditions were deemed appropriate[20].

RESULTS AND DISCUSSION

The conditions represented within this scenario are an attempt to approximate those conditions evident in the original incident given the limitations of the data available, the development of the hazard, the structure and the estimated number of people present. It should be remembered when examining the results produced that we only have several means of comparison: the number of fatalities, the recollections of the survivors and the findings of the NFPA[1].



(a) (b)

Figure 4: Population density diagrams produced by buildingEXODUS (a) one minute and (b) five minutes into the evacuation. Black areas indicate a population density in excess of 4 people/m^2.

The overall model predictions are presented in Table 2. The average TET for this scenario is 5 min 17 sec. After approximately 5 min the first fatalities begin to occur. The average PET is 2 min 46 sec while the average CWT is 2 min 13 sec. This means that on average a person spent approximately 80% of their personal evacuation time caught in congestion. These figures suggest that extremely high levels of congestion occurred very rapidly choking access to the only available exit. This is confirmed by viewing the developing congestion levels using the population density option within buildingEXODUS (see Figure 4). These predictions are in line with the eye witness accounts that suggest severe congestion occurred in the vicinity of the staircase during the evacuation. The average effective travel speed achieved by occupants during this evacuation can be calculated from Table 2 as 0.24 m/s on average.

However, conditions and experiences varied considerably amongst the survivors (see Figure 5 and Figure 6). If two particular individuals are selected from one of the simulations we can determine their experiences. Consider the 50th person to evacuate from the building. This person evacuated the building after 65 seconds spending 38.5 seconds (59% of the evacuation time) in congestion, and was essentially unharmed by exposure to the developing fire atmosphere. If we now consider the 200th person to evacuate, we see a different picture. This person required just over 215 seconds to evacuate, spending nearly 174 seconds (81%) in congestion. In addition this individual was suffered from exposure to the developing fire atmosphere, recording an FIN value of 0.1 and an FIH value of 0.25. This would suggest that this person is likely to have suffered severe burns to exposed parts of the body.

Table 2: Average evacuation statistics for the 10 repeat simulations (range in average values generated across the10 simulations is shown in brackets)

TET (secs)	Number of Fatalities	Average CWT (secs)	Average Distance (m)	Average PET (secs)	Average FIH	Average FIN
317 [315-320]	96 [94-99]	133 [132-134]	40.0 [35.9-37.8]	166 [165-168]	0.2 [0.2-0.2]	0.1 [0.0-0.1]

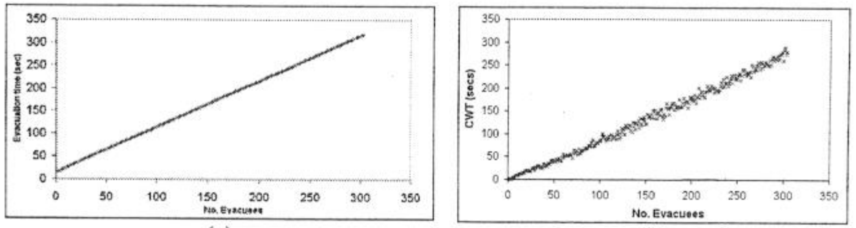
We also note from Figure 6 that the first 150 people to evacuate the building managed to do so without suffering severe exposure to heat (FIH ~ 0.0) and only light exposure to the narcotic gases (FIN < 0.07). However, on average the survivors were affected by the deteriorating environmental conditions, recording an average FIH value of 0.2 and an FIN value of 0.1.

Table 3: Distribution of FIH values amongst survivors for a single simulation

FIH range	Frequency	Cumulative %
0.1 < FIH	173	57
0.1 < FIH < 0.4	58	76
0.4 < FIH < 0.6	30	86
0.6 < FIH < 0.8	26	95
0.8 < FIH < 1.0	15	100

It should be remembered that these values represent averages over 10 simulations. Within any one simulation there may be quite high values amongst the survivors. Presented in Table 3 is the distribution of FIH values amongst the survivors for a particular simulation. In this case while there are 98 fatalities, 41 survivors (i.e. FIH > 0.6) are likely to have suffered serious burn injuries.

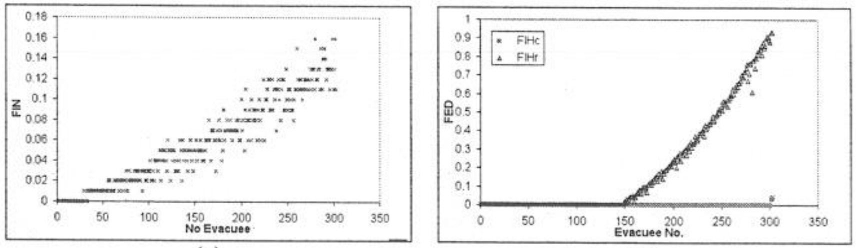
If we assume that individuals with an FED level in excess of 0.1 will have suffered some form of injury, then on average between 150-160 of the survivors are predicted to have sustaining some form of injury (see Figure 6 (a) and (b)) including smoke and toxic gas inhalation and burns.



(a) (b)

Figure 5: (a) The arrival times of the evacuees (b) the congestion experienced by the evacuees.

This compares favourably with the 180 injuries that were recorded during the actual incident. Furthermore, on average these simulations suggest that we can expect some 96 fatalities (see Table 2). This compares with 63 fatalities reported in the actual incident. While there is a discrepancy between the predicted and observed fatality levels, they are of the same order of magnitude.



(a) (b)

Figure 6:(a) The impact of the narcotic gases upon the evacuees. (b) the impact of the temperature and the radiative flux upon the evacuees.

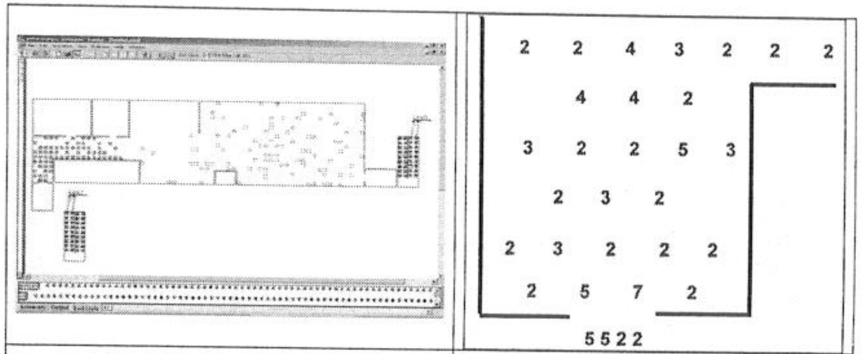
On an official web site concerning the Gothenburg fire, it was reported by The National Board of Health and Welfare for Sweden that;

> *"Most of those who died at the scene had more or less severe burns, but the most common cause of death was carbon monoxide poisoning. Many also had high levels of cyanide in their blood, which in itself could also have been the cause of death". "Those whom the smoke divers succeeded in bringing out at an early stage were suffering from mild smoke poisoning and slight injuries. Of those rescued later, most had severe fire gas poisoning, were unconscious and had more or less severe burns."*[3].

While the official reports acknowledges that heat related injuries occurred, the most important component leading to the high level of fatalities was the occupants exposure to toxic fire gases. The predicted number of fatalities and injury levels is strongly dependent on the accuracy of the imposed fire atmosphere. This in turn is dependent on the experimental data and the nature of the zone modelling and scaling that was applied. The main cause of death in these simulations is heat, whereas the incident reports identify CO and HCN exposure as a significant contributory cause of death. As has already been identified, the fire experiment did not accurately represent the generation and spread of the fire gases. Indeed, HCN was not even represented in the fire experiment. Thus we cannot expect to accurately reproduce the nature of the fire fatalities produced in this incident.

While the toxic gases *contributed* to the predicted fatality levels, the most significant factor driving the number of fatalities was the radiative heat flux generated by the fire (see Figure 6(b)). This problem was exacerbated by the extreme congestion produced during the evacuation. Indeed the average congestion experienced by the fatalities (average CWT for fatalities 281 seconds compared with 133 seconds for the survivors) was far in excess of that experienced by the survivors, indicating of the importance of this factor in determining survivability.

Another aspect of the buildingEXODUS simulations concerns the predicted location of the fatalities. In Figure 7 the locations of the fatalities from one of the simulations is presented. These locations were consistent with all of the simulations examined. It is immediately apparent that the fatalities occurred around the internal exit at the top of the stairs, as was reported in the actual incident. Furthermore, the model predicts that in the immediate vicinity of the main stairwell, bodies were pilled up in some places five and seven high. This observation is similar to reports produced by the fire fighters who reported finding bodies 'piled' around the internal exit leading to the main stairwell. Fire fighters reported that their access to the hall was blocked by a wall of bodies inside the doorway that reached the top of the doorjamb[1]. Finally, while not reported here in detail, other simulations have been conducted to investigate the impact of population size and exit availability[15].



(a) (b)

Figure 7: Fatality locations within the main floor of the Disco building predicted by the buildingEXODUS simulations (a) Starting (open squares) and final locations (filled squares) of the fatalities and (b) the number of bodies pilled up on the floor in the vicinity of the main staircase.

In particular, scenarios were investigated using the same fire conditions but with a population that did not exceed the regulatory compliant population of 150 people. In these cases it was found that it was possible for the entire population to escape without loss of life or severe injury. A further scenario was undertaken, again using the same fire conditions but assuming that an additional staircase was available on the north wall containing the windows. It was assumed that this staircase had similar dimensions to the staircase that was unusable due to the fire. It was found that even with a building population of 400 people, everyone could successfully escape the fire without loss of life.

CONCLUDING COMMENTS

In this paper we have attempted to use CFE tools to forensically analyse a fire scenario similar to the tragic Gothenburg fire incident. It is not claimed that the model accurately reproduces the Gothenburg incident as a key component required for such an analysis i.e. the evolution of the fire is not adequately represented within the model. This was due to a number of factors. Firstly, inaccuracies were introduced by the experimental fire tests due both to scale and discrepancies between the experimental conditions and the original fire conditions. Secondly, the method used to scale up the small-scale experimental fire data are acknowledged to be crude. In addition, the representation of the incident within the evacuation model buildingEXODUS required a number of simplifications to be made that would also have affected the authenticity of the result produced. All of these issues should be considered when analysing the model predictions.

Given these provisos, the model predictions bore a striking resemblance to the events that took place during the actual incident. The model predictions correctly show that the evacuees experienced severe congestion during their attempted evacuation. These predictions show that extreme congestion was experienced around the approach to the only means of escape, the staircase located in the northwestern corner of the building. This fact was highlighted by the NFPA in their assessment of the incident. This congestion was produced by the overloading of the single available egress route caused by the simultaneous arrival of evacuees and the deteriorating conditions. While over predicting the number of fatalities, the model successfully predicted the fatality order of magnitude. Furthermore, the predicted location of the fatalities matched that found in the actual incident. These occurred at the location of greatest congestion: the internal exit located at the top of the staircase. In addition, the number of injuries predicted in this scenario matched those produced during the actual incident. It should be acknowledged that the major cause of the fatalities in these simulations differed from that of the actual incident. Due to the inaccuracies in the fire representation, the major cause of death in the computer simulations was radiative heat, while in the actual incident; inhalation of toxic products was cited as the primary cause of death.

Given the provisos made in regard to the fire data, the assumptions made and the procedure outlined, it is contended that the results produced are satisfactory and have successfully captured the major events and influences of the original incident. Finally, the major conclusion of this work is that the high death toll reported in this incident is a result of the severe level of overcrowding experienced in the hall combined with the loss of one of the means of egress. This analysis has provided insight into the tragic event and an understanding of why so many people died at the Gothenburg incident. Clearly, evacuation and fire simulation analysis of this type has an important role to play in fire investigation.

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REFERENCES

1. Comeau, E. and Duval R.F., "Dance Hall Fire Gothenburg, Sweden, October 28, 1998", Fire Investigations, NFPA, 2000.
2. Ingason, H., Wickström, U., van Hees, P., "The Gothenburg discotheque fire investigation", Proceedings of Interflam 2001, the 9th Int Fire Science and Engineering conf, 17-19th Sept, Scotland, Interscience Comm, pp 965-976, 2001.
3. http://www.sos.se/sos/publ/REFERENG/0112314E.htm
4. http://writer-tech.com/pages/summaries/summgothenburg.htm
5. http://pdm.medicine.wisc.edu/thore.htm
6. http://www.geocities.com/framemethod/goteb.html
7. http://www.crismart.org/pdf/Gothenburg_Fire.pdf
8. http://www.wsws.org/news/1998/oct1998/swe-o31.shtml
9. Wickstrom, U. and Ingason, H., "The Gothenburg Discotheque Fire Reconstructed on a Model Scale", BrandPosten, Fire Technology, SP Sweden, 22, June, 2000.

10. Wickstom, U.,"The Discotheque Fire – Why did so many die?", BrandPosten, Fire Technology, Sp Swedish National Testing and Research Institute, 22, June, 2000.
11. Ingason, H., "The Discotheque Fire – Model Trials Confirm the Hypothesis " , BrandPosten, Fire Technology, SP Sweden, 22, June, 2000.
12. Thureson, P.,"The Discotheque Fire – the stairwell was full of combustible material", BrandPosten, Fire Technology, SP Sweden, 22, June, 2000.
13. Personal communication with H. Ingason of SP, Sweden, 2002.
14. Peacock, R.D., Forney, G.P., Reneke, P., Portier, R., and Jones, W.W., "CFAST, The Consolidated Model Of Fire Growth And Smoke Transport", *NIST Technical Note 1299, U.S. Dept. of Commerce, Technology Administration, NIST, 1993.*
15. Jiang, H., Gwynne, S. Galea, E., Lawrence P., Jia, F. and Ingason, H., "The Forensic Investigation of Fire Incidents using Computational Fire Engineering Techniques and Experimental Data", To be published, CMS Press, University of Greenwich, 2003.
16. Gwynne, S., Galea, E., R., Owen, M. Lawrence, P. J. and Filippidis, L.," "Review of modelling methodologies used in the simulation of evacuation", *Journal of Building and the Environment, 34, pp441-749, 1999.*
17. Gwynne, S., Galea, E., R., Owen, M. and Filippidis, L "A systematic comparison of model predictions produced by buildingEXODUS evacuation model and the Tsukuba pavilion evacuation data", Applied Fire Science, Vol. 7, No. 3, pp235-266, 1998.
18. Gwynne, S., Galea, E., R.,Lawrence, L. and Filippidis, L., "Modelling Occupant interaction with fire conditions using the buildingEXODUS evacuation model", Fire Safety Journal, 36, pp 327-357, 2001.
19. Galea, E. R., Owen, M., and Lawrence, P., Computer Modelling of Human Behaviour in Aircraft Fire Accidents, Toxicology, Vol. 115, Nos. 1-3, 63-78, 1996.
20. Galea, E.R. Gwynne, S. Lawrence, P. Filippidis L., and Blackshields, D., "buildingEXODUS V4.0:User Guide and Manual", Univ of Greenwich, 2003.
21. Purser, D.A., "Toxicity Assessment Of Combustion Products", *The Sfpe, Handbook Of Fire Protection Engineering (3rd Edition), Ed:Dilenno, P.J., Drysdale, D., Beyler, C.L., Walton, W.D., Custer, R.L.P., Hall, J.R., and Watts, J.M.W., National Fire Protection Association,Quincy,Ma, pp (2-83)-(2-171), 2002.*
22. Purser, D.A. "Modelling Time To Incapacitation And Death From Toxic And Physical Hazards In Aircraft Fires", *Conference Proceedings No: 467, Aircraft Fire Safety, NATO-AGARD Sintra, Portugal 22-26 May, pp41-1 - 41-12, 1989.*
23. Jin, T And Yamada, T.,"Irritating Effects From Fire Smoke On Visibility", *Fire Science And Technology, Vol. 5, No.1, pp79-90, 1985.*
24. Jin,T., "Visibility Through Fire Smoke", *Report Of Fire Ins Of Japan #42,Sept 1976.*