

FIRE AND FLOODING RISK ASSESSMENT IN SHIP DESIGN FOR EASE OF EVACUATION

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ABSTRACT

Large-scale flooding (following a collision or grounding event) and fire onboard ships constitute the principal hazards that may lead to passenger evacuation. If these hazards develop into an uncontrollable situation, it must be ascertained a priori that all people on board can be evacuated safely. Evacuation analysis should therefore be aimed at developing a system (a minimum standard of “Evacuability”) that guarantees this assertion to an acceptable level by utilising advanced consequence analysis tools for flooding, fire and evacuation within a risk assessment framework. Developing such a system will ensure focus on passenger safety in a systematic and all embracing way that safeguards against the consequences from the principal hazards leading to abandoning a ship or mustering to a safe refuge onboard, by providing an active link between the two. In this respect, one can deal cost-effectively with design, operation, regulation and training issues. This paper summarises current developments regarding the use of flooding, fire and evacuation analysis tools in the context of risk assessment for ship design.

KEY WORDS: fire, flooding, evacuation, risk-based design, fire zone modelling,

INTRODUCTION

In the wake of the Estonia (Ro-Ro/passenger ship) disaster, trends of largely increased capacity of passenger ships, with people onboard now ranging up to 6,000, have brought the issue of effective passenger evacuation, it being the last line of defence in an emergency, to the centre of attention of the maritime industry worldwide. However, the process of evacuating a large passenger ship is a very complex one, not least because it involves the management

of a large number of people on a complex moving platform, of which they normally have very little knowledge. These characteristics make ship evacuation quite different to evacuation from airplanes and buildings.

To address the risk associated with passenger evacuation at sea, the term Evacuability (passenger evacuation performance capability) has been devised entailing a wide range of capabilities that encompass evacuation time, identification of potential bottlenecks, assessment of layout, life saving appliances, passenger familiarisation with a ship’s environment, crew training, effective evacuation procedures/strategies, intelligent decision support systems for crisis management and design/modification for ease of evacuation. From a technical point of view, the mass evacuation of thousands of people from an extremely complex environment with unknown inaccessibility problems exacerbated by (potentially co-existing) incidents such as progressive flooding, fire/smoke and the inherent uncertainty deriving from unpredictability of human behaviour, is a problem with severe modelling difficulties at system, procedural and behavioural levels.

With this in mind, the following sections of the paper seek to illustrate how available prediction tools for fire (LESSFIRE), flooding (PROTEUS), and evacuation (EVI), can be utilised in assessing and evaluating risk from the point of view of human life safety, one of the key design and operation priorities. EVI incorporates basic capabilities that can be used to estimate the effects of fire and flooding in the evacuation process. In both cases, data from external tools that address flooding and fire hazards independently (outside the evacuation environment) is required. This data is then imported into the EVI evacuation environment as additional semantic information for the agents (evacuees). The agent model condenses human behaviour in an evacuation to a small set of crucial characteristics such as speed and awareness. A hazard within the evacuation environment will affect these characteristics changing the performance of the agents.

All tools (PROTEUS, LESSFIRE and EVI) originate from the SSRC and are at different stages of development and validation, as it will be described hereafter.

FLOODING RISK ASSESSMENT

Collision and/or stranding are the largest contributors to the risk of sink/capsize for passenger-carrying vessels. The probability of survival and eventually the time to sink and/or capsize are crucial factors in determining the actual level of safety of a ship design. Whilst the former can be reasonably estimated using empirical-based methods, the latter (time to sink/capsize) is strongly determined by the geometry, topology and status of the internal compartmentation and openings (including doors, ducts, valves, etc) in addition to the random sea environment.

The behaviour of a damaged vessel, and the progression of floodwater through it in a random seaway form a highly non-linear dynamic system, the behaviour of which can only be assessed through time domain simulation. Building on this view, the University of Strathclyde began to develop the first-ever numerical model of this kind already 15 years ago. Since then, this model has been amply validated and calibrated through its application in both research and consulting work, before arriving at its current version, PROTEUS-3.1, *Jasionowski,(2001)*. PROTEUS is capable of simulating the vessel's behaviour (6-dof motions at zero or forward speed of intact or damaged ships, the latter of single or multiple compartment configuration) as well as the progression of transient and progressive flooding through any damage compartment configuration and any shape and position of the openings through which flooding can occur. In addition, a number of non-linear effects can be incorporated, such as wave generated drift, wind loading, instantaneous hydrodynamic forces and moments, dynamic effects of cargo shifting, impulsive ramming excitation, moorings, among others.

In PROTEUS, the complex behaviour of floodwater is modelled with a simplified method, developed as an alternative to RANSE CFD techniques. This technique, adopted within PROTEUS 3.1, derives from an approximation of floodwater transfer by pendulum-like movement driven by ship-motion-related/gravity acceleration field and constrained by internal compartment geometry on one hand and undisturbed floodwater free surface on the other. Thus, fully non-linear interactions between the ship and floodwater, treated as two interdependent, albeit separate, dynamical systems is represented meaningfully and with sufficient engineering accuracy. The output from PROTEUS, including time histories of the vessel motions and accelerations, as well as floodwater mass, elevation and attitude in every modelled compartment of the ship, is incorporated into the evacuation model environment (EVI) as explicit semantic information with the following effects:

- **Deck inclination:** Asymmetric flooding will heel the ship making it more difficult to walk and reducing the speed of agents;
- **Ship Motions:** Dynamic motions will affect peoples' orientation and movement capabilities, consequently, agents will move more slowly, take wrong decision or may fall over;
- **Inaccessibility:** Flooding will make some areas of the ship inaccessible. This means that for personnel on lower decks certain evacuation routes may become unavailable.

The simulation imports motion and flooding data, which is processed to give deck inclination to the horizontal (level) position. Using inclination, a correction factor is applied to the maximum walking speed of an evacuee (agent) in the decision stage of the agent update algorithm. The speed correction factor is based on the results of research undertaken in the MEPDesign project – this has been described in detail in *Vassalos et al, (2001)*. Thus, flooding data is used to control the awareness and walking speed of agents, reducing it as they become more affected by (immersed into) the floodwater, as illustrated in Figure 1.

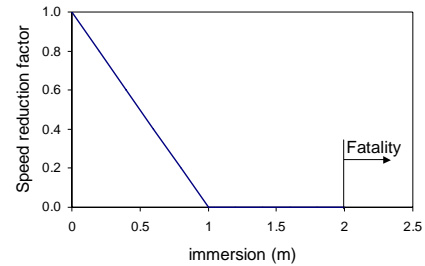


Figure 1: Speed reduction factor due to effect of floodwater, based on conservative engineering judgement pending further validation by experimental data

All the above-listed effects, would affect the time needed for orderly assembly and eventually, the time needed for safe evacuation of all people on board. For any pre-determined flooding scenario, the integrated simulation environment allows a total evaluation of the safety objectives. If these are not met, the effectiveness of potential solutions can then be re-evaluated until an acceptable solution is found.

FIRE RISK ASSESSMENT

Despite the fact that prevention and mitigation of the most common fire-related events onboard ships are extensively addressed by current prescriptive regulations, fire and explosion continue to be among the major hazards to ship operations. Currently, fire safety in ship design is addressed by compliance with the prescriptive regulations of SOLAS, dealing with issues of prevention, suppression and escape, among others. These regulations have a major impact on the resulting designs, in terms of layout, functionality and costs, in some cases inhibiting development of innovative, equally safe but potentially more cost-effective solutions. Such issues are important in all sectors of the maritime industry today. At the same time, the increased level of understanding of fire physics and of the influence of fire on human behaviour as well as advances in fire modelling has encouraged the use of performance-based design codes in other industries, particularly aviation and civil architecture. The same trend is being observed in the Maritime Industry.

This is reflected in the new regulation II-2/Regulation 17 of SOLAS, which allows the use of performance-based fire engineering methods to demonstrate that design solutions not complying with some of the prescriptive regulations are as safe as an equivalent prescriptive design. This approach is commonly referred to as the “equivalence” principle, according to which the design solution, referred to as an “alternative” design, is set to achieve the same fire safety

objectives and comply with the same functional requirements as an equivalent prescriptive design. Despite being more time consuming and expensive than the traditional prescriptive approach, performance-based ship design may lead to potentially safer, innovative, attractive and more cost-effective design solutions.

Available statistics, for instance *Mater et al.* (1997), indicate that more than 60% of all fire casualties occur in general cargo ships, bulk carriers and oil tankers. Passenger ships (including ro-ro ferries) account for just 6% of all fire incidents. In spite of this, high numbers of people carried on board put newer passenger ships at significant risk of life loss (in relation to other ship types) arising from fire or flooding. Moreover, current trends in ship design suggest that alternative design solutions developed with performance-based methods for fire safety will be a feature mainly of passenger ships; hence the focus on fire safety from the point of view of passenger survival alone.

There is still very limited experience with the use of alternative design for fire safety and there are reasons for this: prescriptive design is easier (training is not needed), and fire-engineering tools are neither easily available nor easy to use, among others. However, as far as passenger ships are concerned, there are many potential areas for exploiting benefits of alternative design (large internal promenades, larger than currently permitted public spaces, alternative ventilation strategies, alternative escape and evacuation arrangements, “safe area” concept, among others).

For those cases, the performance criteria are associated with safety of human life and mitigation of material damage to the ship for a specified fire event. Thus, parameters describing the hazards associated with fires (such as temperature, heat fluxes, toxic contamination and visibility obscuration) must be predicted with sufficient accuracy for large and small spaces of simple and non-standard geometries, e.g. with large horizontal or vertical dimensions (corridors, vehicle decks, staircases, atria, engine rooms). On the other hand, the level of uncertainty in the associated parameters necessitates that variational studies be conducted to ascertain the level of sensitivity of the results. Thus fire-engineering tools must be able to provide quick solutions even for large applications, ranging from few spaces to complete vertical fire zones spanning several decks.

In terms of alternative design and arrangements for fire safety as stated in SOLAS Regulation 17, the use of consequence-analysis tools in conjunction with appropriate criteria for evaluating human life safety is essential. The approach adopted in this respect, is described next.

Evaluation of human life safety

It is well established that when evaluating the consequences of fire effluent to human life, the crucial criterion for life safety is that the time available for escape should be greater than the time required. The time available for escape is the interval between the time of ignition and the time after which conditions become untenable such that occupants can no longer take effective action to accomplish their own escape. Untenable conditions during fires may result from:

- Inhalation of asphyxiant gases; these may cause loss of consciousness and ultimately death resulting from hypoxic effects, particularly on the central nervous and cardiovascular systems,
- Exposure to radiant and convective heat, and
- Visual obscuration due to smoke.

The above represent the fire hazards and can be imported and distributed in time and space into the evacuation environment (EVI) as explicit semantic information for the agents. These include concentrations of CO, CO₂, and O₂, as well as temperature, radiant heat flux and optical density directly affecting –at each time step– the awareness and walking speed of the evacuee (simulation agents). In order to estimate the effect of the fire hazards, an approach presented by *Purser (2002)* was adopted (summarised next); the approach is based on the concept of Fractional Effective Dose (FED, for toxicity and heat) and Fractional Effective Concentration (FEC, for visibility). The FED and FEC are values indicating the human vulnerability to the cumulative effects of exposure to heat and toxic gases as well as the level of visibility in a space. Their values are calculated for each agent individually and are used to control walking speed and awareness and determine the point at which an agent becomes fatally injured, as illustrated in Figure 2. An overview of the calculation method of the FED and FEC is provided next.

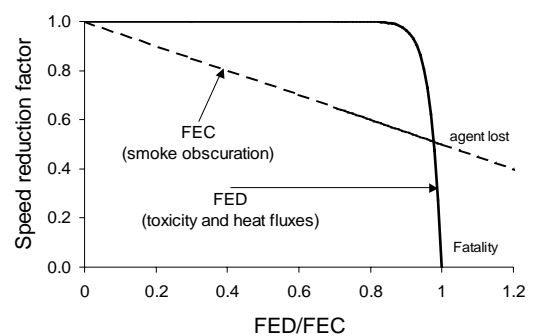


Figure 2: Speed reduction factor due to fire hazards, based on conservative engineering judgement pending further experimental data

Toxicity Model

The Fractional Effective Dose of incapacitation (FED_{IN}) due to asphyxiant gases, namely carbon monoxide CO and carbon dioxide CO₂, as well as due to depletion of oxygen O₂, is given by the following expression:

$$FED_{IN} = \left[\sum_{i=1}^{i=2} \frac{K \times [CO]^{1.036}}{D} \Delta t \right] \times V_{CO_2} + \left[\sum_{i=1}^{i=2} \frac{1}{\exp[8.13 - 0.54(20.9\% - \%O_2)]} \Delta t \right]$$

Where, Δt (in *min*) is the time increment, [CO] (in *ppm*) is the average concentration of CO over the time increment (Δt), K and D are constants depending on the activity of the person (taken as 8.29250×10^{-4} and 30, respectively corresponding to persons at light work).

Carbon dioxide (CO₂), like carbon monoxide, is universally present in fires. Although CO₂ is not toxic at concentrations of up to 5%, it stimulates breathing. This hyperventilation, apart from being stressful, can increase the rate at which other toxic fire products (such as CO) are taken up. The increased uptake resulting from carbon

dioxide induced hyperventilation will significantly reduce time to incapacitation and death. To take this effect into consideration, the value of FED_{CO} at each time increment (first term of the above equation) was multiplied by a frequency factor (V_{CO_2}) to allow for the increased rate of asphyxiant uptake due to hyperventilation, given by the following expression:

$$V_{CO_2} = \frac{\exp(0.1903 \times \% CO_2 + 2.0004)}{7.1}$$

Where $\%CO_2$ is the percentage of CO_2 in the evaluated compartment. The second term in the equation represents the FED for oxygen hypoxia, where $(20.9\% - \%O_2)$, is the percent oxygen vitiation over the time increment (Δt).

Convective and radiant energy model

The body of an exposed occupant may be regarded as acquiring a “dose” of heat over a period of time. There are three basic ways in which exposure to heat may lead to life threat: hyperthermia, body surface burns, and respiratory tract burns. For use in the modelling of life threat due to heat exposure in fires, it is necessary to consider only two criteria: the threshold of burning the skin, and the exposure where hyperthermia is sufficient to cause mental deterioration and, therefore, threaten survival. A short exposure to a high radiant heat flux or temperature is generally less tolerable than a longer exposure to a lower temperature or heat flux. A methodology based on additive FEDs similar to that used with toxic gases may be applied and, providing that the temperature in the fire is stable or increasing, the total fractional effective dose of heat acquired during an exposure can be calculated according to the following expression:

$$FED_{Heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t$$

Where, t_{Irad} (in *min*) is the time to burning of skin due to radiant heat. The tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2 . Below this incident heat flux level, exposure can be tolerated for 30 minutes or longer without significantly affecting the time available for escape. Above this threshold value, the time to burning of skin due to radiant heat decreases rapidly according to the following equation:

$$t_{Irad} = 1.33(\dot{q}_{rad})^{-\frac{4}{3}} \text{ for } \dot{q}_{rad} \geq 2.5 \text{ kW/m}^2, \text{ where } \dot{q}_{rad} \text{ (in } \text{kW/m}^2\text{) is the radiant heat flux.}$$

Calculation of the time to incapacitation (t_{Iconv} , in *min*) under conditions of exposure to convective heat from air containing less than 10% by volume of water vapour can be made using the following equation:

$$t_{Iconv} = K_1 T^{K_2},$$

where, T is the temperature in $^{\circ}C$. The value of the constants (K_1 and K_2) depends on the extent of clothing, taken as 4.1×10^7 and -3.6 , respectively for fully clothed subjects.

Smoke Obscuration Model

The visual obscuration effects of smoke based on the concept of fractional effective concentration is given by the following equation:

$$FEC_{smoke} = OD/0.2 \text{ for small enclosures and travelling distances (visibility up to 5m) and,}$$

$$FEC_{smoke} = OD/0.08 \text{ for large enclosures and travelling distances (visibility up to 10m).}$$

Where, OD (in m^{-1}) is the optical density of the smoke. In this equation, the smoke concentration is expressed as a fraction of the concentration considered to significantly affect escape efficiency. If the total FEC_{smoke} reaches unity, then it is predicted that the level of visual obscuration would be sufficient to seriously affect escape attempts.

Enclosure fires and fire modelling

Most of the fires occurring onboard ships are fires in enclosures. They can develop in a multitude of different ways, depending on the geometry, ventilation and fuel availability, and include the following factors/phenomena:

- Sources of fire and ignition,
- fire plume and ceiling jet,
- smoke layer and lower layer,
- vent flows and mechanical ventilation,
- boundary heat transfer,
- target heating and response.

These phenomena are addressed with varying degrees of detail by different fire models. There are three prevalent deterministic approaches in fire engineering, including regression analysis, zone models and field modelling, now mainly finite-volume methods. All of the approaches can be used for particular purposes.

In finite-volume methods, the flow domain under consideration is divided into a large number of control volumes. The basic laws of mass, momentum, and energy conservation are applied to each of the control volumes along with appropriate initial and boundary conditions for the calculation domain. In relation to fire modelling, a number of sub processes need to be modelled, including combustion, turbulence, radiative heat transfer, soot transport and production, pyrolysis and flame spread.

In zone models, each compartment is discretised into one or few control volumes. In two-zone models, each of the control volumes is composed of two gas layers. The upper layer developing beneath the ceiling contains the buoyant gases and products of combustion. The lower layer is of relatively fresh air that remains near the floor. The equations for mass and energy conservation are solved for both layers for every time step in order to determine the average temperature and smoke composition within each zone. Momentum conservation is not applied; instead, velocities across openings are calculated from pressure differences. The coarse discretisation used in such models puts many physical processes on the “sub-grid” level. Such processes are modelled using approximate fits to experimental data or results of higher-accuracy calculations.

The main difference between zone and finite-volume models is the accuracy of discretisation. From a practical viewpoint, finite volume models require more computing resources and expert knowledge, not only in physics and chemistry, but also in numerical methods and computer science. In addition, data preparation, calculations and post-processing are very time consuming. Nevertheless, such methods may be the only way forward when dealing

with complex physics or geometry, or where adequate empirical correlations do not exist for simpler models.

Zone models have proved to be an effective tool for estimating enclosure fire conditions. This, in addition to quick data preparation and quick numerical solutions, have led to increased popularity of these models in fire safety engineering. However, use of zone models requires that the user is well acquainted with the assumptions made and the limitations of the approach. In the next sections, a general description of a zone approach is given together with validation studies and illustration of the features of the method and possible ways for improvement.

ZONE MODEL

LESSFIRE, is the acronym for the fire/smoke suite of programs at SSRC/SaS for fire engineering analysis, which includes the model presented here - a multi-compartment zone model capable of accommodating large numbers of compartments (depending on available computer resources) with multiple connections (vents and ducts). The input required by the model consists of geometrical data together with locations and heat release rate time histories of fires. Composition of walls and properties of different fuels are stored in databases. The output is propagation of hazardous factors through a ship, including high temperature and heat fluxes, toxic combustion products and visibility obscuration. These data are used in the evacuation simulation for assessment of the influence of fire on evacuation.

The method uses coarse grids (one or more control volumes per compartment) and large time steps (one to ten seconds). Gas in each control volume is assumed to consist of two well-mixed uniform gas layers (one of which may be of zero volume) with a horizontal interface between them.

For each gas layer, *mass conservation* equation is solved by integration in time of all sources of mass, including, for upper gas layers, products of combustion from fires, mass entrained in the fire plumes from lower layers and mass fluxes through vents. For lower gas layers, mass sources include mass loss due to the entrainment in the fire plumes and mass transfer through vents.

Energy conservation equation is solved in the form relating average pressure rise in a compartment to heat sources due to convective, conductive and radiative heat transfer. Convective transport of energy includes similar terms to those in mass transport: heat of combustion from fires, enthalpy pumped by the fire plumes from lower into upper layers and convective heat flux through vents. An additional term arises due to convective heat exchange between the gas and solid walls of enclosures.

Additionally, *transport equations for gaseous species* are solved. A total of eight conservation equations of gaseous components are considered, including the species from the ambient air (oxygen, carbon dioxide, water and inert species) and combustion products (unburned fuel, carbon dioxide, water, carbon monoxide, soot, hydrogen chloride and hydrogen cyanide).

Flow rate through *vents* is defined by integration of Bernoulli's equation for a streamline over the vent area. Calculated mass and heat fluxes are redistributed between the gas layers of the compartments on each side of the vent, assuming that a flux originating in a lower or upper layer must terminate in the lower or upper layer, respectively, of

the other compartment, due to the influence of buoyancy. Forced ventilation by fans is also included.

For calculation of *heat conduction* between compartments or to the ambient atmosphere, every wall, floor and ceiling is subdivided into an arbitrary number of segments. To model compartments of arbitrary geometries, a data structure similar to the cell-face-based connectivity structure of unstructured finite-volume grids is employed. In the input to the code, each wall segment is specified by its corner points and indices of the two adjacent compartments. A geometrical pre-processor developed to prepare such data uses a CAD model as an input.

Wall segments can consist of several layers of different materials, continuous or separated by air layers. The individual material layers can be treated either as thermally thin, with uniform temperature throughout the layer (steel plates) or thermally thick, conducting heat with a finite rate (insulation). In either case, the heat fluxes to the segment surfaces, provided by the radiative and convective heat transfer calculations, serve as boundary conditions for the temperature distribution calculations inside segments; the calculated surface temperatures are used as boundary conditions for convection and radiation calculations in the adjacent compartments.

The *burning rate* of fires is prescribed as time histories of heat release rate under unlimited oxygen supply and corrected taking account of ventilation conditions: for a fuel-rich fire, the burning rate is restricted by the available oxygen supply. *Radiative heat transfer* is modelled between surface panels, gas layers and fires with a discrete transfer method. Further details can be found in *Shigunov (2004a)*.

Because the described model includes the most essential physics and is inherently conservative, it can provide numerical results of acceptable accuracy regarding integral characteristics, such as average temperatures, vent flows between compartments, radiative heat exchange between gas layers, walls and fires, heat conduction through walls and convective heat transfer between gas and solid walls. The largest drawback of the model follows from the coarse discretisation: many processes become of "sub-grid" scale and must be modelled. The most important among them are mixing effects, for instance, turbulent mixing between fire plumes and ambient air or between opposite fluxes in vent flows. Other important "sub-grid" phenomena are unresolved such as transient flows in long (corridors) and high (staircases) compartments. Some of these problems are discussed below.

Plume Entrainment Modelling

As hot gases rise from a flame, the colder surrounding air is entrained into the plume. The mixture of combustion products and air reaches the ceiling of a fire compartment and forms a layer of hot gases. The model that estimates the entrainment of ambient air into the fire plume defines how quickly the thermal interface will descend and what characteristics the upper layer will have, e.g. its temperature and species content. The code LESSFIRE uses several empirical fits relating the mass entrainment rate to the interface height and heat release rate from fires. Although some details of these fits differ, all of them provide comparable results. For isolated unobstructed fire plumes, these fits usually provide accurate results. However, if the plume interacts with obstacles or other fluxes, they may not

work well. If the fire plume is obstructed, for instance by stairs in a stairwell, the mixing of the plume with the ambient air becomes very strong; in this case, dedicated experiments are necessary to provide more suitable approximations for zone models. Another example is turbulent mixing between opposite fluxes in vent flows. It is modelled in zone models in a way similar to the fire plumes, underestimating strong mixing of the upper and lower layers.

An example when these empirical formulae are not valid is the experiments by *Steckler et al. (1982)* for a single compartment connected with the ambient atmosphere through a door and window. The burner was located at several positions (in the centre of the room, near walls, in the corners etc.) either near the floor or at an elevated height. Several constant heat release rates were produced. The door width varied from 0.24 to 0.99 m. Detailed comparison of calculations with measurements can be found in *Shigunov (2004b)*; some of the results are shown in Figure 3 and 4 (dependencies of flow parameters on the door width and heat release rate from the fire, respectively).

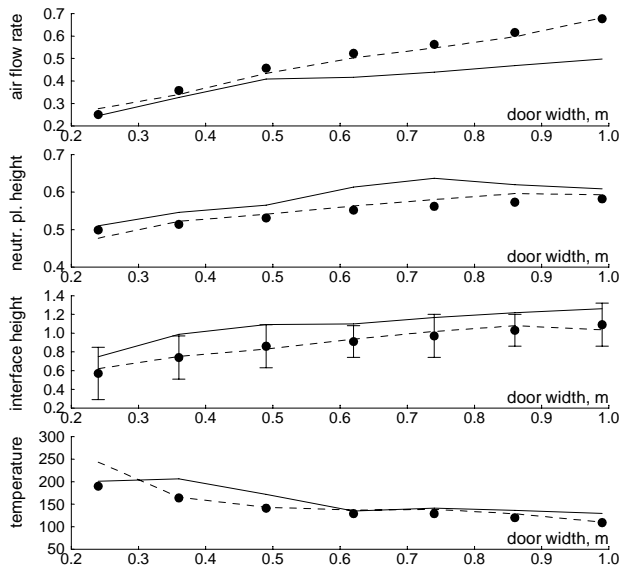


Figure 3: Results of calculations depending on the door width compared with experiments for the middle-room fire of 62.9 kW

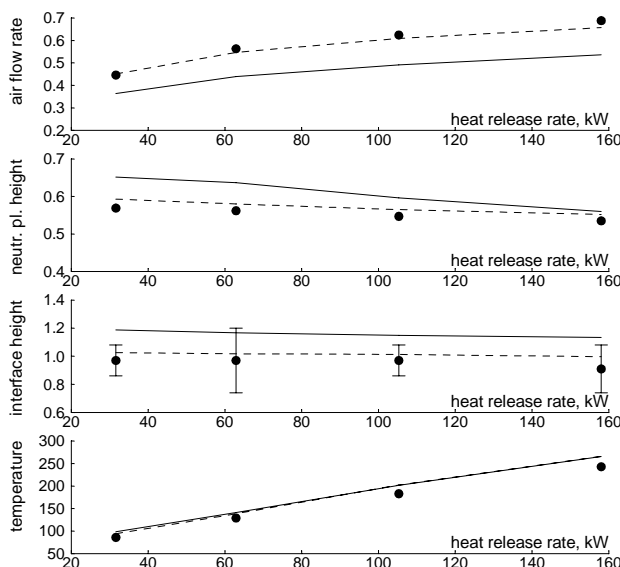


Figure 4: Results of calculations depending on the heat release rate in comparison with experiments for a middle-room fire

The figures show air mass inflow rate through the door in m/s, neutral plane height, non-dimensionalised by the door height, thermal interface height in m and mean temperature of the upper layer in °C. Solid lines and signs (the latter with uncertainty bars) correspond to calculations and experiments, respectively. Large difference between calculations and measurements arises due to the influence of the door flow on the fire plume. The air inflow deflects the fire plume from the vertical direction and increases mass entrainment (by a factor 2 to 3.5, according to the results presented). Although a dedicated study is required to model this phenomenon, a simple correction was used here, which considerably improved the comparison. The effective “height” of the plume used in the empirical formulae was increased to reflect the non-verticality of the fire plume. The deflection was taken proportional to the mass inflow rate through the door. The results calculated with this correction are shown with dashed lines in the same figures.

Transient Flows in Corridors

Another important limitation of zone models follows from the assumption of the horizontal interface between gas layers. This assumption over-estimates the speed of propagation of combustion products and heat from fires in multi-room configurations, especially if some of the compartments have large horizontal dimensions (for instance, corridors). This drawback can be reduced through further subdivision of such compartments into smaller “rooms” connected through vents. To test the method for complex layouts including corridors, the experiments by *Cooper et al. (1982)* were simulated.

The geometry, shown in Figure 5 consists of a burn room connected through a corridor with a lobby. The door from the corridor to the lobby can be closed, and additional separations can be installed in the corridor at the locations shown with dashed lines, leading to a number of different test configurations. A methane burner used as a heat source produced several constant or linearly increasing in time heat release rates. Additionally, the width of the door from the burn room to the corridor was systematically varied. Figure 6 shows results for a test case with the full working area (burn room, corridor and lobby), full width of the door from the burn room to the corridor and a linearly varying heat release rate from 0 to 300 kW in 10 min.

Lines and circles represent results of calculations and measurements, respectively. The top plot shows time histories of the thermal interface height in the burn room (solid line and filled circles) and lobby (dashed line and empty circles). The second plot shows vertically averaged temperature increment (from ambient) for the same locations. The third and fourth plots show pressure difference at the ceiling level across the door between the burn room and the corridor, and the total averaged heat loss to walls due to heat conduction, respectively.

The large difference between the calculations and measurements for the heat loss at the first 60 seconds of the test is due to the fact that the estimations of the heat loss in experiments did not account for the heat content in the fire plume and ceiling jet, which accommodate a significant fraction of the total heat release at early times of burning.

Therefore, the heat loss obtained from the measurements is likely to be overestimated. The correspondence between the calculations and experiments for other variables seems satisfactory. Comparison of calculations with experiments for all test cases can be found in *Shigunov (2004b)*.

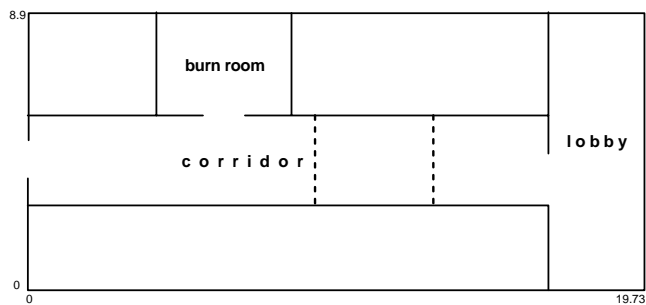


Figure 5: Multi-room configuration

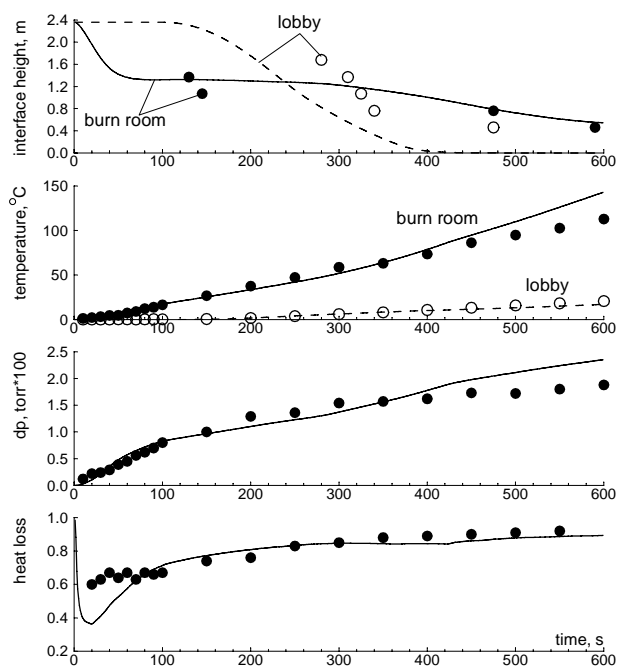


Figure 6: Results for multi-room configuration

In accommodation spaces of ships, the most relevant problem to be addressed in a fire situation is the propagation of combustion products and heat from a fire through many corridors and stairways. The following case illustrates how such cases can be addressed with the model presented. The geometry shown in Figure 7 consists of two decks with identical layout connected through a staircase. The corridors are modelled as series of connected rooms.

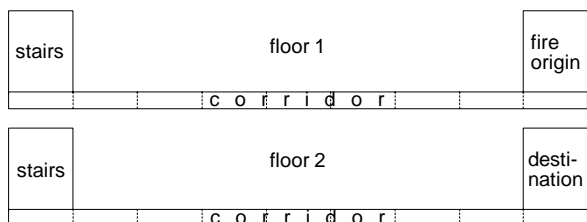


Figure 7: Test case with a staircase and two long corridors

Results of calculations are shown in Figure 8 and 9. The three lines on each of the plots correspond to the room of fire origin located on the first floor (solid lines), staircase connecting the first and second floors (dashed lines) and destination room located above the fire origin room on the second floor (dash-dotted lines). The top plots show time histories of the thermal interface height and the bottom plots the temperature of the upper gas layer.

In Figure 8, the left-hand plots were obtained with the “fine” discretisation shown in Figure 7. In the room of fire origin, the thermal interface stabilises at the height of about 1.5 m for about 10 min. During this time, combustion products are pushed into the first-floor corridor and further to the staircase. The thermal interface in the staircase forms at 5 min. after beginning of the burning and descends very rapidly, totally filling the staircase in about 3 min. After this, the thermal interface in the room of fire origin starts to descend rapidly and reaches the floor in about 10 min. after ignition. At the same time, gas from the upper layer is unable to pass through the corridor on the second floor, therefore the destination room remains uncontaminated.

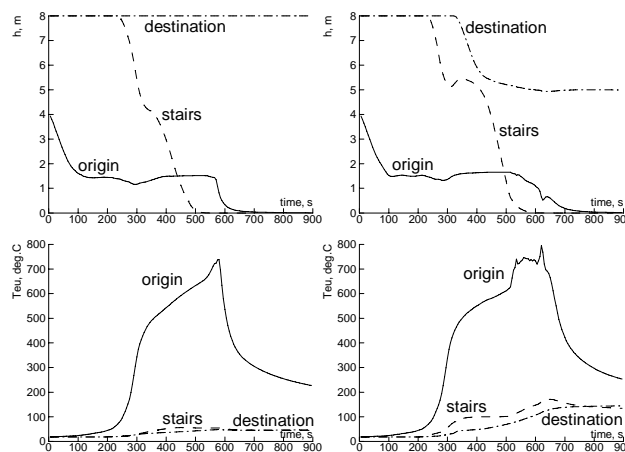


Figure 8: Thermal interface height (top) and temperature of the upper gas layer (bottom) for the room of fire origin, stairs and destination room; left- and right-hand plots correspond to the accurate and coarse discretisations, respectively

For comparison, the right-hand plots in Figure 8 show results obtained with a simplified model, where each of the corridors was simulated as one compartment. The results look very similar for the room of fire origin and slightly different for the staircase, while the solution for the destination room is quite different – the reduced model predicts filling of this room with smoke, not shown in the more accurate solution.

In the case considered, the fire self-extinguished because of the absence of the sources of fresh air. To study fire development under well-ventilated conditions, windows were introduced in the room of fire origin and the destination room. The results are shown in Figure 9. As above, the left-hand plots correspond to the more accurate discretisation of the corridors while the right-hand plots were obtained with a “coarse” geometrical model representing each of the corridors as one compartment. A steady-state solution is going to be achieved in this case, with the thermal interface stabilised at the levels of about 1.7 and 2 m from the floor in the room of fire origin and the

destination room, respectively, and the staircase filled up with smoke.

The reduced model shows results similar to these for both the room of fire origin and the destination room, while fails to predict the total filling of the staircase with smoke. The temperature of the upper gas layer is calculated with the reduced model also well both for the fire origin and destination rooms. It seems that an accurate sub-division of corridors into smaller “compartments” is essential for obtaining more accurate results with zone models.

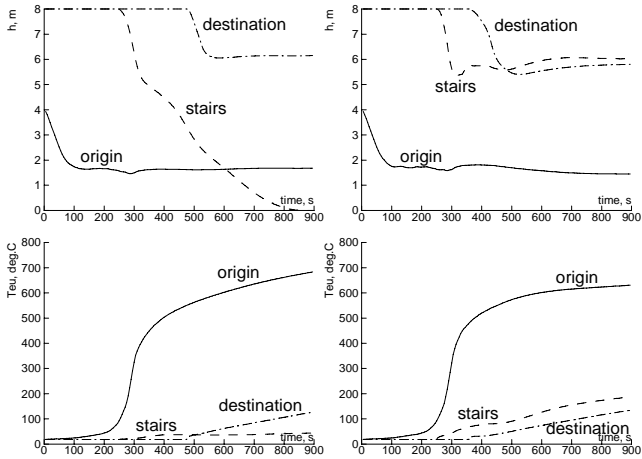


Figure 9: Similar to figure 6, but for a well-ventilated case

Case Study – Fire on the Vehicle Deck of a RoRo Ferry

Due to the combination of large amounts of light flammable fluids and sources of ignition, and impossibility of effective partition, vehicle decks represent one of major fire hazards onboard Ro-Ro ferries. The fire load due to burning of a car or a pool of fuel may be very high and the proximity of other vehicles provides favourable conditions for further development and propagation of a fire. On the other hand, the access of oxygen is limited, therefore the fire may self-extinguish in a short time. The influence of different ventilation conditions on fire on a vehicle deck was studied in model experiments at the Swedish National Testing and Research Institute, see Larsson *et al.* (2002). Numerical simulations of the tests were carried out in Shigunov (2004a); a short summary is provided here.

One of the models represents a rectangular box of dimensions 11.425 by 2.786 by 0.625 m equipped with a ventilation fan, exhaust ventilation shaft, gate, two windows and drainage scuppers. A wood crib used as a fire source provided heat release rate of about 400 kW in free burning conditions. Comparison of calculations with measurements is shown in Figure 10-12 for cases 4 (ventilation shaft and scuppers open), 5 (ventilation fan on, ventilation shaft and scuppers open), 6 (two windows open) and 9 (loading gate and scuppers open); numbers of tests correspond to those in Larsson *et al.* (2002).

The heat release rate from fire was calculated as $\min[Q_{p,free}, Q_{p,max}(z_i - z_f)/h_f]$, where $Q_{p,free}$ is the free-burning heat release rate and $Q_{p,max}$ is its maximum for the fully developed fire; z_i is the height of the thermal interface, and z_f and h_f are the ordinate of the bottom of the crib and its height, respectively. This formula follows from the

assumption that the part of the crib in the upper, contaminated gas layer is excluded from the burning region. Although rather simplistic, this assumption works well enough in this case.

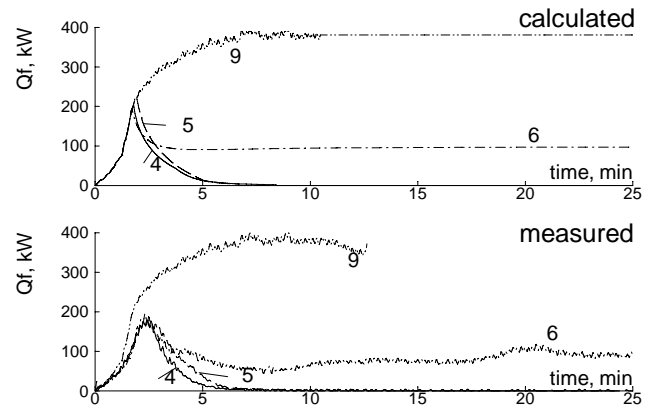


Figure 10: Calculated (top) and measured (bottom) heat release rate

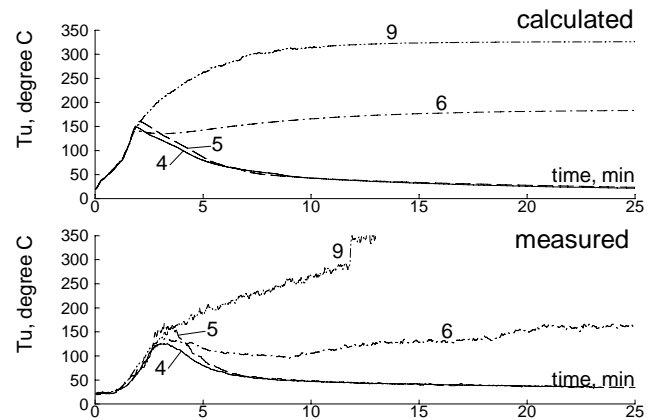


Figure 11: Calculated (top) and measured (bottom) temperature of the upper gas layer

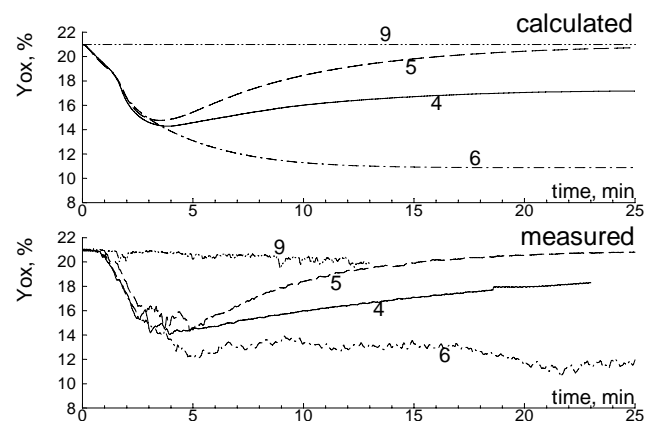


Figure 12: Calculated (top) and measured (bottom) mass fraction of oxygen in the upper gas layer

The heat release rate from the fire increases in a similar way in all test cases at the beginning. In tests 4 and 5, the heat release rate starts to decrease after the air becomes contaminated with the combustion products, and the fire extinguishes in about 6 min. In test 6, the oxygen supply from the windows is sufficient to support the heat release

rate at about 70 kW, while in test 9, the supply of air together with the exhaust of combustion products through the gate is sufficient to support the free burning rate. The temperature of the gas in the upper layer is closely related to the heat release rate. In tests 4 and 5, it starts to decrease at about the same time as the heat release rate, in test 6 it raises slowly due to the burning supported by the air supply through the windows, and in test 9 it raises much more than in the other cases. Mass fraction of the oxygen in the upper gas layer drops to about 14% in 4 min. in all test cases. In test 6, it continues to decrease slowly; in test 4, it raises slowly after the fire extinguishes, due to leakage of air in the model, while in test case 5, it raises more quickly due to the active ventilation.

Vehicle deck - Two Decks Layout

The two-deck layout shown in Figure 13 consists of two similar decks connected through a ramp compartment 4. The central casing subdivides each deck longitudinally. In calculations, each deck was divided into three smaller "compartments" connected through vents shown with dashed lines. Deck 1 corresponds with the ambient atmosphere through gates in the stern. Fire of 70.0 MW is located in the middle of the "compartment" 1. Results of calculations are shown in Figure 14-16.

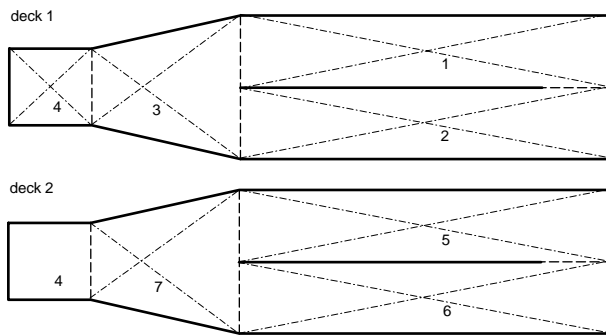


Figure 13: Two-deck layout

In each figure, the top plot shows the height of the thermal interface in m, the middle plot the temperature of the upper layer in °C, and the bottom plot the mass fraction of oxygen in the upper layer in per cent; the numbers 1-7 correspond to the numbers of the compartments. It follows from the results that the most dangerous situation is when all vents are open. In this case, the oxygen supply through the gate is sufficient for supporting the unlimited heat release rate from the fire. Maximum temperature in compartment 1 is 400°C, and temperatures in the other compartments are sufficient for igniting other vehicles. The case with the decks connected through the ramp room is also rather dangerous, although the fire extinguishes in this case. The smoke from the fire fills all compartments, and maximum temperatures are similar to or higher than the temperatures in the ventilated case.

For reference, computing time on a Pentium II computer was 3.0 to 6.0 seconds for one hour of real time with time step of 5 seconds.

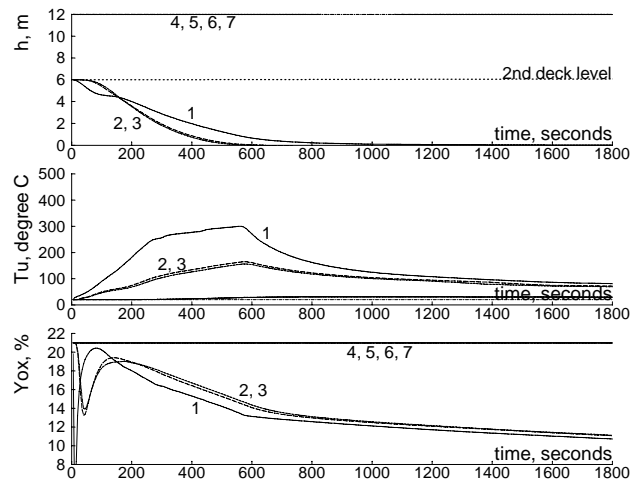


Figure 14: All vents closed

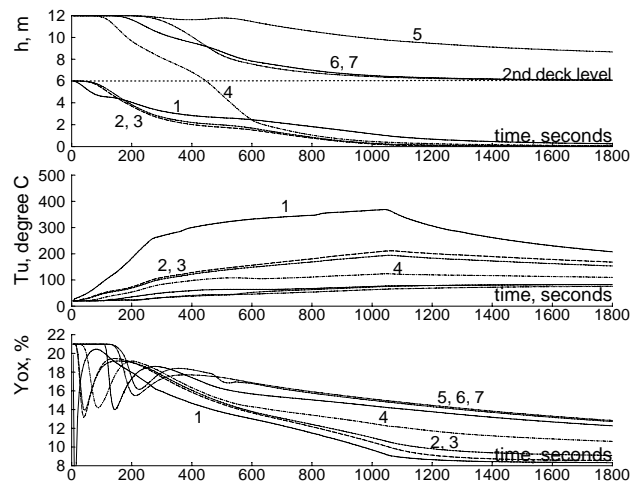


Figure 15: Decks are connected through the ramp compartment

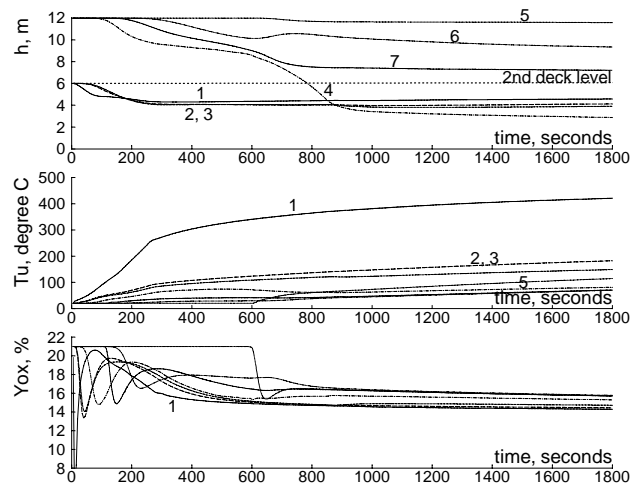


Figure 16: Gate to the outside open and decks are connected through the ramp compartment

CONCLUDING REMARKS

This paper highlights the integration of first-principles simulation tools for flooding and fire (PROTEUS and LESSFIRE, respectively) into an advanced evacuation model environment (EVI) and presents a workable model of

fire engineering analysis. The integration of such tools allows for an explicit and direct evaluation of ship and human life safety in any given flooding and/or fire accident situation (scenario). This type of capability is essential if a “holistic approach” for ship design is to be adopted, particularly in relation to large passenger ships (see SLF 47/8). This approach entails that (large passenger) “ships must be able to withstand a stipulated damage (extent of damage) threshold and still safely return to port under its own power.” Even if the casualty threshold is exceeded, “a ship is to remain habitable for a minimum time (3 hours) to allow for safe and orderly abandonment.”

The above reflects the trends toward goal-based standards and highlights the merits of a risk-based design methodology. This is particularly useful when dealing with innovative ship design concepts and alternative design and arrangements. In such cases, quantitative risk analysis is the only reliable route to ensure that an appropriate level of safety (equivalent to an acceptably low level of risk) and the set safety goals (e.g. safe area) are achieved.

With regards to fire zone modelling, the following conclusions can be made:

- Due to its simplicity and high speed, both in calculations and preparation of data, the fire zone model presented in the paper, represents a useful tool for assessment of alternative designs.
- The method relies on many empirical models for “sub-grid” effects and, therefore, requires additional preparation work in cases where such models are not available. Besides, the over-estimation of the speed of propagation of combustion products and heat, especially in corridors, needs additional care during discretisation.
- Examples included in the paper illustrate some of the weaknesses of the method and demonstrate possible ways of addressing them.
- The remaining uncertainties (e. g. convective plume flows in stairwells and atria) need additional empirical data for further refinement of the model. Traditionally, such data were gathered from full-scale or model experiments, which are expensive. A more promising way now seems to be the application of accurate numerical methods such as finite volumes, to particular problems in order to provide the necessary empirical fits.
- In addition to verification of zone model assumptions, finite-volume calculations can be used to solve particular small-scale problems of fire safety, such as heating up of structural components, testing of bulkheads for smoke and heat propagation resistance etc. Currently, such methods are also under development and testing at the SSRC/SaS and will be presented elsewhere.

The physiological effects of fire hazards (and flood water) on human behaviour (and their effects on the evacuation process) are the biggest unknowns in the evaluation of human life safety using first-principles simulation tools. This gap could only be addressed through experimental/empirical data, which at the moment is very limited. In the mean time, conservative engineering judgement offers the only workable way.

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