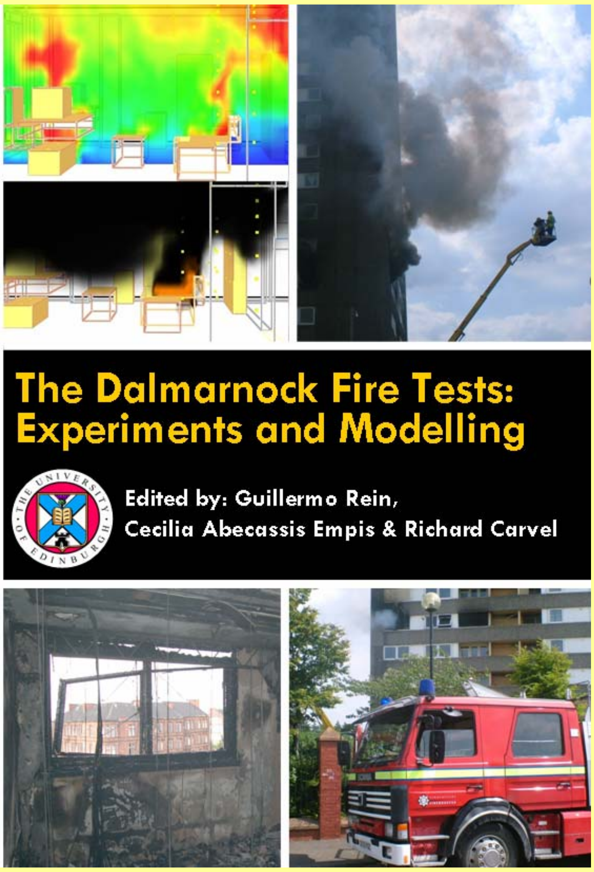
The Dalmarnock Fire Tests: Experiments and Modelling
Edited by G. Rein, C. Abecassis Empis and R. Carvel



**Published by the School of Engineering and Electronics,
University of Edinburgh, 2007.
ISBN 978-0-9557497-0-4**

1. Introduction to FireGrid

By Stephen Welch, Asif Usmani, Rochan Upadhyay, Dave Berry, Stephen Potter and José L. Torero

Introduction

Retrospective analysis of every emergency poses the recurrent question: was the response adequate? The answer is usually complex, but invariably acknowledges that better information would have led to more effective response. This was brutally illustrated, for example, in the World Trade Center attacks when emergency crews continued operations totally oblivious to the impending collapse of the towers, and history is littered with examples of tragic failures in emergency response resulting from simple lack of knowledge of this type (Berry *et al.* 2005).

Consider instead if fire and rescue services could be provided with detailed information on the way an incident is unfolding, augmented with predictions of anticipated hazards. FireGrid is focused on the development of a novel approach which aims to fulfil this vision, involving the following:

- Sensing: data from the emergency is collected and relayed
- Modelling: robust integrated simulation tools use this data to predict event evolution
- Forecast: simulations are achieved faster than real time
- Feedback: processed results provided to active response systems/emergency services
- Response: an intelligent command & control system coordinates all intervention

In FireGrid these functionalities will be linked by the 'grid' technologies that give the project its name. Grid technologies dynamically discover and co-ordinate distributed computing resources to work on solving a common problem.

It is envisaged that FireGrid will operate in several modes. In 'design mode' the modelling and decision support systems are exploited to enable building designers to simulate many possible fires 'in silico'. By linking the fire simulations with building plans and models of fire, structure and egress, the designers will be able to see how appropriate their designs are for different possible emergency scenarios.

In 'emergency response mode', FireGrid links the sensing information, building models and stored simulations into the decision support system. This will facilitate rapid intervention, with effective mitigation of fire incidents before they develop into full-scale emergencies. It will also provide building control teams and fire-fighters full information

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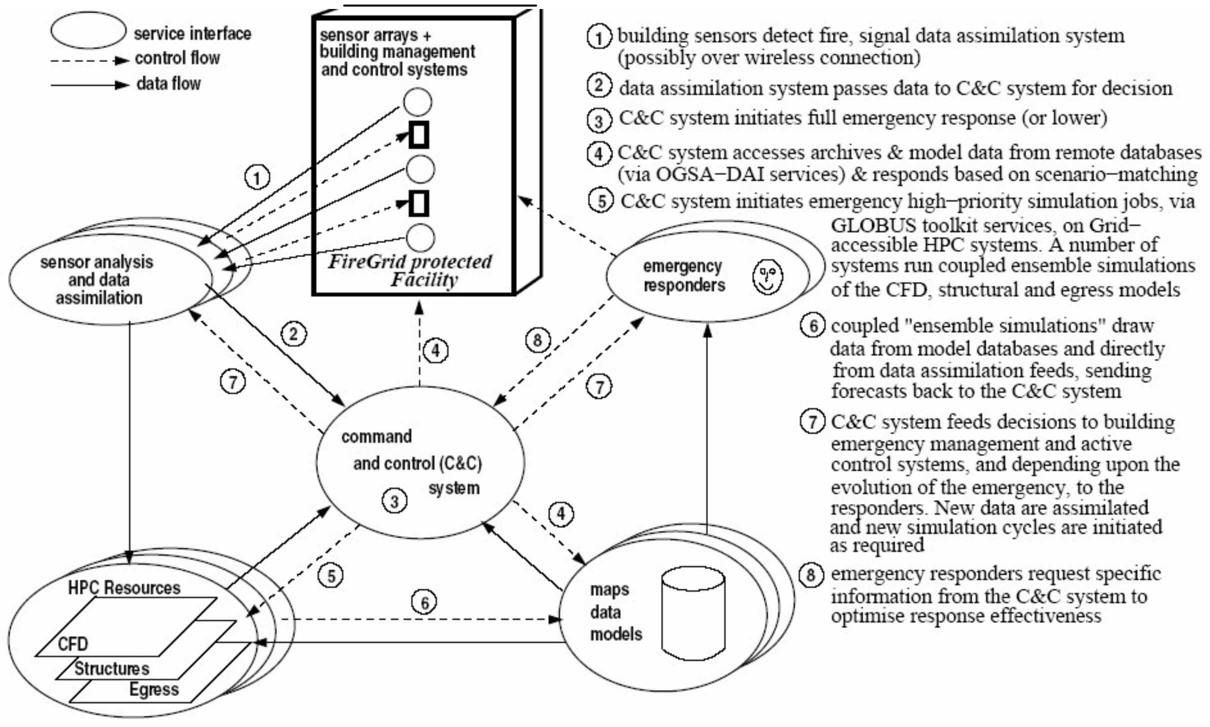
about any fires that do develop. Ultimately, this mode will include a forecast capability, allowing the decision support system to run computer simulations faster than the fire itself develops. These simulations are only likely to be feasible if guided by input from the sensors, and may be conducted at various levels of complexity, to provide redundancy. Hence if fires have not been caught early and eliminated, FireGrid can provide emergency responders with critical information on the conditions in the building and potential future hazards, such as collapse, thereby guiding their intervention strategies.

Finally, the system will be used in a 'research mode' to *study* fire emergencies, and a 'training mode' is to be developed. The latter could be used in fire-fighter training, to give an interactive test and response of decisions made in simulated fire emergencies.

The immediate application of the system is for fire-related emergencies, but the methodology could ultimately be extended to handle hazard mitigation more generally, including CBRN (Chemical/Biological/Radiological/Nuclear) incidents which may result from arson or terrorism, and the results of severe natural disasters, i.e. earthquakes, floods, etc. Figure 1 shows a possible activation scenario for a fire emergency.



① building sensors detect fire, signal data assimilation system (possibly over wireless connection)

② data assimilation system passes data to C&C system for decision

③ C&C system initiates full emergency response (or lower)

④ C&C system accesses archives & model data from remote databases (via OGSA–DAI services) & responds based on scenario–matching

⑤ C&C system initiates emergency high–priority simulation jobs, via GLOBUS toolkit services, on Grid–accessible HPC systems. A number of systems run coupled ensemble simulations of the CFD, structural and egress models

⑥ coupled "ensemble simulations" draw data from model databases and directly from data assimilation feeds, sending forecasts back to the C&C system

⑦ C&C system feeds decisions to building emergency management and active control systems, and depending upon the evolution of the emergency, to the responders. New data are assimilated and new simulation cycles are initiated as required

⑧ emergency responders request specific information from the C&C system to optimise response effectiveness

Figure 1: Technology integrations required to develop FireGrid

The key benefits of the project stem from integration of the relevant technologies (see Figure 2), including: advanced modelling tools for fire, structural response and egress, sensor networks, grid infrastructure and High-Performance Computing (HPC) resources to perform super-real-time computations, and decision support systems to translate simulation output into operational instructions for deployment of active systems and intervention by human responders. Each of these areas is, and has been, a topic of

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research and development in its own right, in some cases over many years; the novelty of the project is in their integration, with the significant advances entirely dependent on the coupling, *e.g.* the speed-up of model predictions via sensor linking.

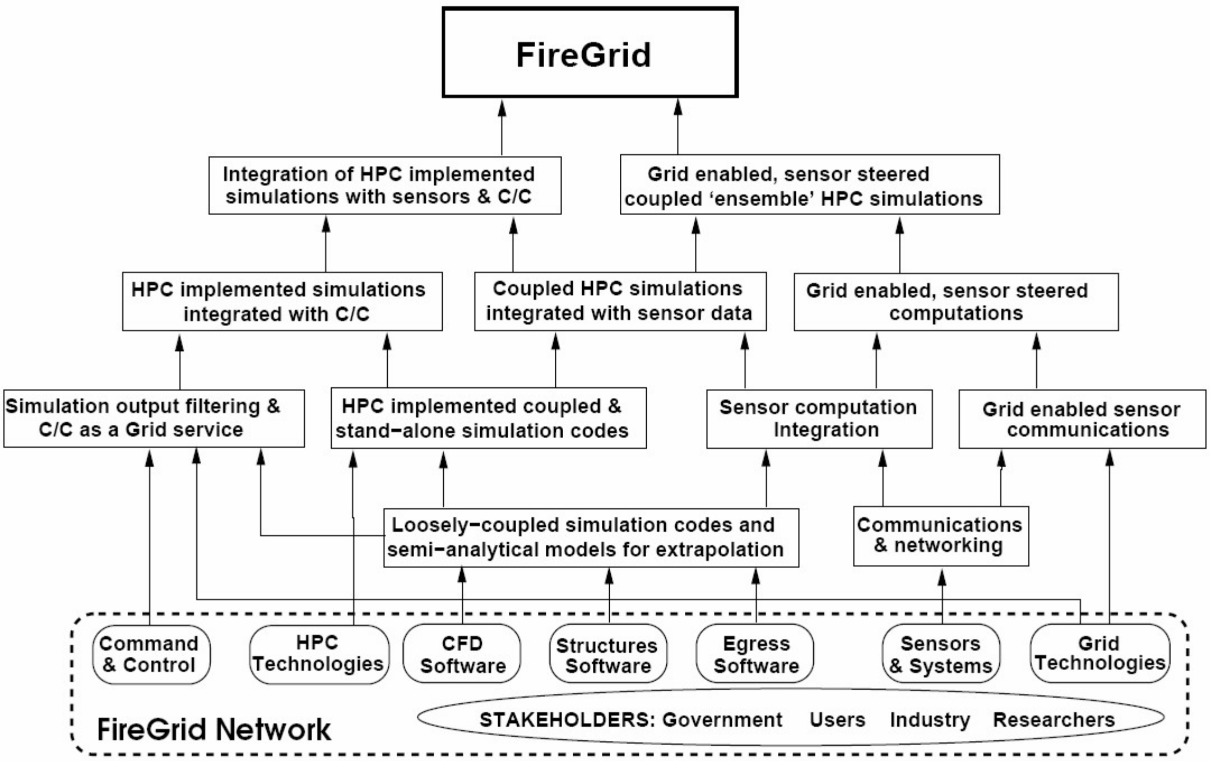

Figure 2: Possible FireGrid activation scenario

In order to fulfil the vision of FireGrid, fundamental research is required into all aspects of the problem and a great deal of work is required on the relevant integration tasks. In each case the initial focus is to establish generic frameworks and procedures which provide a robust platform for the development and deployment of a system of this nature, rather than the generation of a commercial tool. Wherever possible, freely available software and open access codes are being adopted and the results are being widely disseminated. This paper explores a number of the research themes encompassed in the project and discusses the potential application of the FireGrid system in full-scale fire scenarios, of which the Dalmarnock tests are representative.

Technology integrations

The main innovation in the project is the broad integration of a range of independently-developed technologies to create a powerful new generic tool. A schematic of the integration strategy is shown in Figure 2, together with brief descriptions of the components. Specific novel aspects include data assimilation strategies which update and correct the model predictions by exploiting real-time sensor data, the 'loose' coupling of diverse modelling tools, deployment of robust self-organising wireless sensor networks, high-speed processing using grid/HPC infrastructures with 'on-demand' access of remote resources, and application of intelligent command and control (C&C) algorithms. The Dalmarnock fire tests have provided a driver for initial work on several of these integrations, and a useful test-bed for assessment and discussion of each aspect, but with an essential difference in the substitution of sensor-linked simulations by a human 'expert'. The key topics are examined in more detail below, prior to an analysis of their potential application using illustrations and examples taken from the Dalmarnock tests.

Sensor linking

One of the key technical breakthroughs sought in the FireGrid project is the speed-up and correction of the model 'prediction' by coupling to sensor outputs, so as to achieve the essential capability for super-real-time response, a technique known in general as 'data assimilation'. By 'prediction' it is meant in the broadest sense the evolution of the conditions in the building, i.e. fire development and structural response, together with the egress and intervention behaviours. However, in most of the following discussion the emphasis is on the fire-sensor coupling, which is a challenging area in its own right. One only has to refer to the parallels in meteorology, where weather forecasts exploit measurements on atmospheric conditions, to appreciate the scale of this undertaking. Moreover, the timescales of fire events are typically much shorter than meteorological occurrences, so the predictions are required to be generated much more quickly.

The implementation and application of a data assimilation framework is being explored at the most basic level by examining the performance of simple simulation tools for the prediction of vertical flame spread (Cowlard *et al.* 2007), and also for the more advanced models, including zone and computational fluid dynamic (CFD) models, focusing on smoke filling problems. Some aspects of these studies are described below after a general introduction to 'data assimilation'.

Data assimilation

'Data assimilation' is the technique whereby measured data is directly accumulated into the model state, i.e. by correcting or replacing the predictions of the model, which are otherwise purely theoretical. It is one of the methods which can potentially be used to incorporate sensor measurements into computational models, and it is widely used in weather forecasting applications. The general principles of the concept are first discussed, followed by illustrations of the exploitation of the technique in various applications.

Figure 3 shows a cartoon illustrating the 'actual state' (state of reality) to be studied. Also shown is the 'model state', which may in principle be the result of both the simulation using a model that describes the actual state and the observed state that is described by the measurements made on the system. In the discussion, 'state' refers to the collection of all the physical variables that are chosen to represent the system at any time. Clearly neither the model state nor the observed state can provide a complete description of the actual state of the system, since there exist modelling assumptions and computational errors, as well as experimental uncertainties, respectively. Since both the model state, as

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well as the observed state, are compromised by uncertainties, it is useful to characterise them both using probabilities.

A schematic of one type of data assimilation concept is illustrated in Figure 4. The model can in principle predict the future evolution given the current state of the system. At a particular instant, experimental data is also being collected that is used to adjust the model predictions. The updated model state is called the 'analysis state' and the updating step is called the 'analysis step'. This step involves an application of Bayes' theorem. Another novel approach is Dynamic Data Driven Modelling (Michopoulos *et al.* 2005).

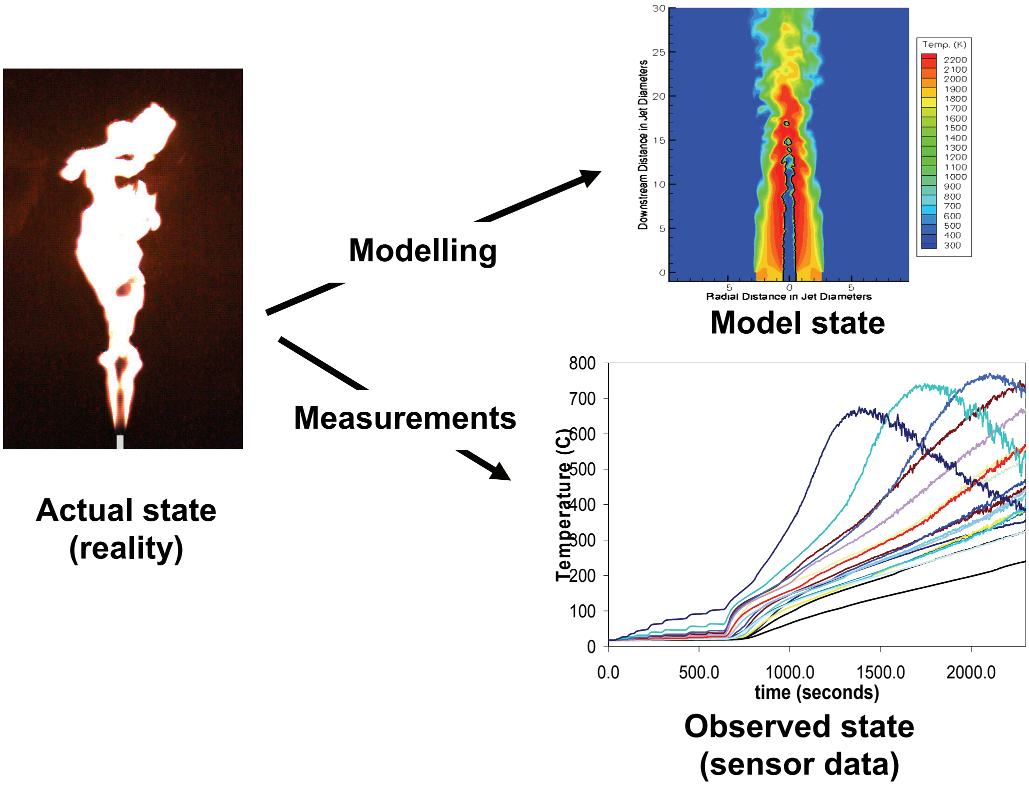

Figure 3: Illustration of the actual state and approximate representations of the actual state based on a model (model state) and direct observations or measurements (measured state)

Figure 5 shows a schematic representation of the data assimilation concept, applied in the context of fire development. The relationship between successive attempts to predict the evolution of the problem and the true conditions is apparent from the flame length curves.

One can infer some of the limitations of data assimilation methods for fire applications by considering their use in weather prediction. It is a very well known fact that advance forecasts of the weather can be rather inaccurate. This is due to the inherent non-linearity of the Navier-Stokes equations describing the fluid flow and the highly sensitivity to initial conditions, and transition to chaos, that effectively precludes long-term predictions. Indeed, due to this reason, data assimilation is an absolute necessity in this field.

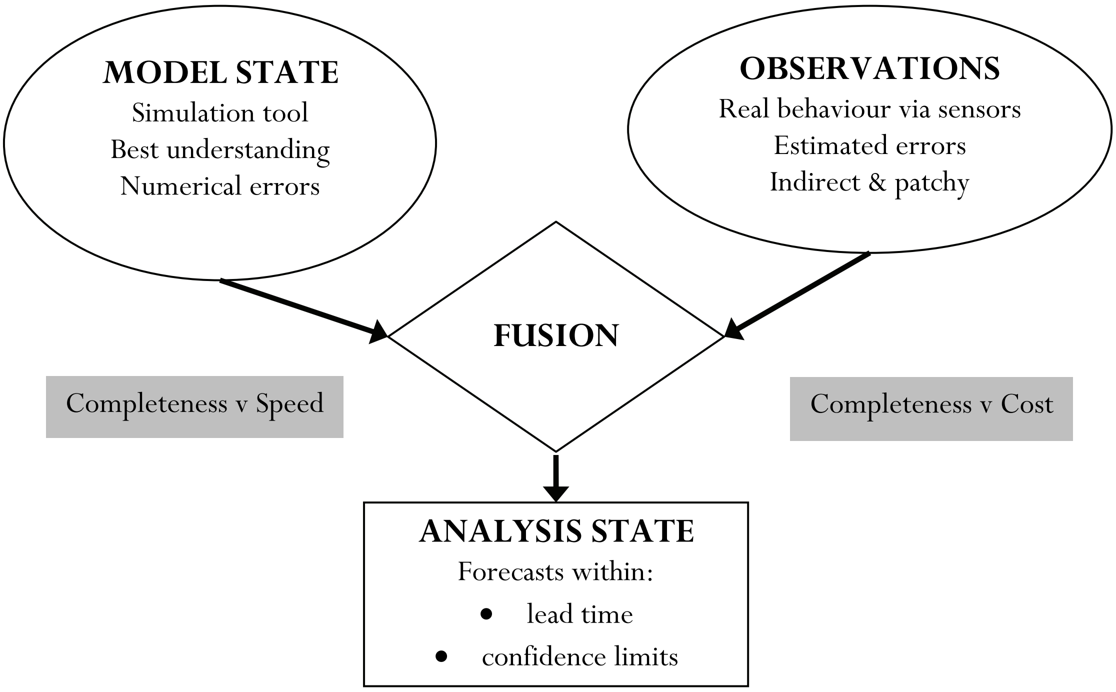

Figure 4: Schematic of the data assimilation concept

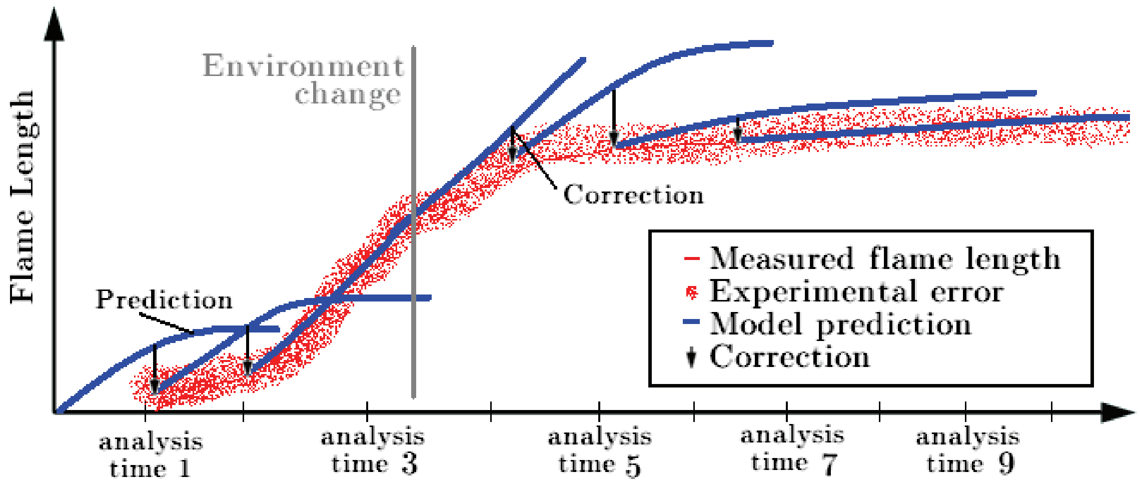

Figure 5: Schematic showing data assimilation concept as applied to prediction of flame length evolution (Cowlard *et al.* 2007)

Whilst the equations describing the fluid motions in weather and the motion of smoke and gases in a fire are fundamentally the same, there are several significant differences between the requirements for prediction of fire and weather. These relate to the various scales of the problem. In weather forecasting, the length-scales are usually of the order of kilometres and time-scales are of the order of hours. The lead time, *i.e.* the longest time between issue of the warning and the actual occurrence of the event, in weather forecasting is of the order of a few days (AMS 2007). In fires, the equivalent scales under study, i.e. those between the incipient stage and the evolution of hazardous conditions,

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are spatially of the order of metres and temporally of the order of minutes, for example the fire development in the Dalmarnock fire tests (cf. Chapters 3-4). When considering an entire building, the time- and length-scales are clearly yet larger, but still nowhere near those which are of relevance to weather predictions. It is apparent that fire is typically a fast and dynamic phenomenon, hence the effective lead time also has to be very short to allow for effective intervention and evacuation. So by analogy, data assimilation in fire is fundamentally similar to that used in weather forecasting but at much smaller space- and time-scales. The data assimilation philosophy therefore needs to be subjected to much greater scrutiny prior to exploitation in fire applications.

Application of data assimilation at the level of a full-scale fire test, exemplified by Dalmarnock, is highly challenging; here, two simplified applications are discussed.

Flame spread case study

In order to test the linking of sensor data and fire model predictions in one of the simplest possible scenarios coupled measurements and predictions have been made for a bench-scale test on upward flame spread (Cowlard *et al.* 2007). PMMA slabs are adopted, of dimension 150 mm wide by 200 mm high, and 40 mm thick, confined within vertical shields, see Figure 6. This case was particularly selected because the flame spread process is fairly well characterised and known to be generally steady and repeatable.

Figure 6: Plan view of experimental setup (Cowlard *et al.* 2007)

Despite the relatively simple test specification, the phenomena involved in upward flame spread are nevertheless complex, and highly coupled. For example, the spread rate depends on the heat transfer to the surface, which is typically dominated by radiation; since the latter is strongly influenced by the species breakdown in the flames, including soot yields, and these derive from the complex fuel decomposition/pyrolysis, the overall spread rate is a function of the detailed gas-phase conditions, and vice versa. Simulation of this process is therefore a significant challenge in its own right, demanding comprehensive modelling tools in which the constituent phenomena are coupled at as fundamental a level as possible. It is possible to develop such models, particularly where the experiment can be repeated *ad lib* for model calibration and validation, but they lack generality (Welch & Marshall 2003). However, when sensors are used, and the process is monitored in real time, a different strategy presents itself. A basic modelling framework can be adopted, with tuneable constants being adjusted in real time as the flames spread, *i.e.* a form of self-learning. Provided that the overall modelling framework is sufficiently general, this type of method will be a much more flexible tool which does not necessarily require a detailed knowledge of the properties of the participating combustible materials, etc., *i.e.* could in principle even be applied to new or unknown materials.

For the demonstration of this concept, temperature and heat flux measurements have been adopted, together with optical measurements using a PIV system and CCD cameras. The cameras and surface thermocouples provide estimates of the evolution of the pyrolysis front. Flame height is measured with CCD cameras, and a PIV system is used to characterize the flowfield. A simple upward flame spread velocity correlation is adopted. This is purely algebraic and links flame characteristics and pyrolysis evolution. The measurements are continuously fed to the computations so that projections of the flame front location can be established for each instant in time. Rapid convergence between the experiments and the predictions is attained, cf. Figure 7.

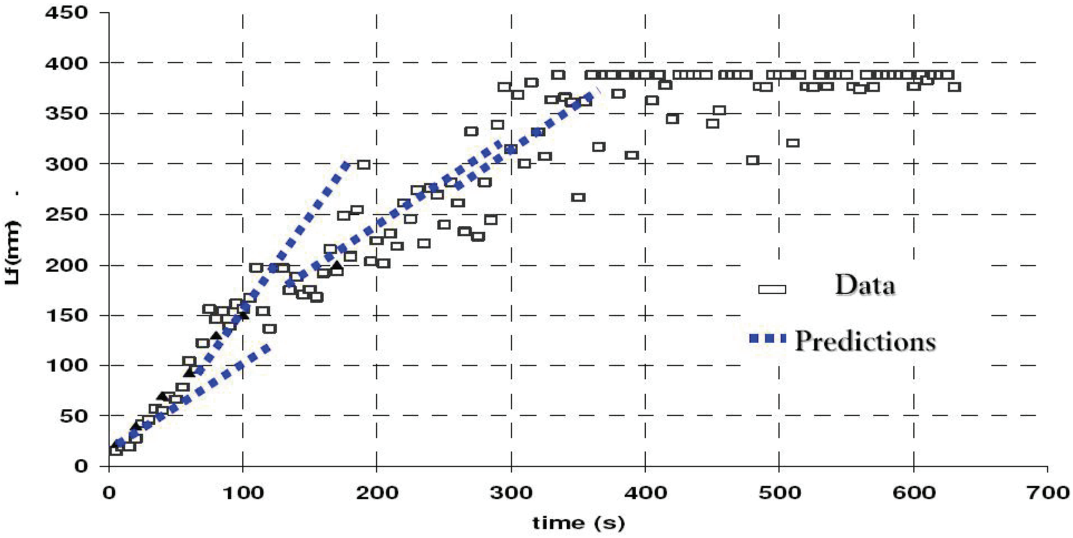


Figure 7: The evolution of predicted and measured flame lengths (adapted from Cowlard *et al.* 2007)

Clearly, this scenario is far removed from the conditions which might exist in a real-world fire, such as the Dalmarnock tests, both in terms of the simplification of the fire spread scenario, enforced by the physical constraints on flame spread, and the high degree of sophistication of the measurements. Nevertheless it is an important first step towards demonstrating that it is possible to achieve super-real-time predictions via a methodology based on both a fundamentally-based conceptual model, and critically, a degree of self-learning only made possible by real-time monitoring.

Smoke movement case study

An altogether different scenario is considered for the second case study, *i.e.* a smoke filling problems. Here, different modelling tools are appropriate, the scope encompassing simple zone models which track the hazard evolution essentially as a 1D layer development problem, and CFD models which give a full 3D description of the fire conditions. It is apparent that model correction is relatively straightforward in the former case, layer heights simply being adjusted to reflect the measured values derived from vertical thermocouple rakes in the measurement space, but much more challenging for the latter, where true data assimilation cannot be avoided. Both techniques are being explored in the context of full-scale demonstration experiments, including compartment fires and more complex scenarios.

Model integrations

A range of models are available for different aspects of the problem, including simulation of fire development, structural response and human egress. In each case there is a broad span of model sophistication, ranging from simple correlations and analytically-based approaches, to detailed simulation tools based on numerical algorithms, e.g. Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM). It is beyond the scope of this paper to discuss all of these in detail, but some of the main issues associated with the coupling of fire-structure and fire-egress are discussed below.

Fire-structure coupling

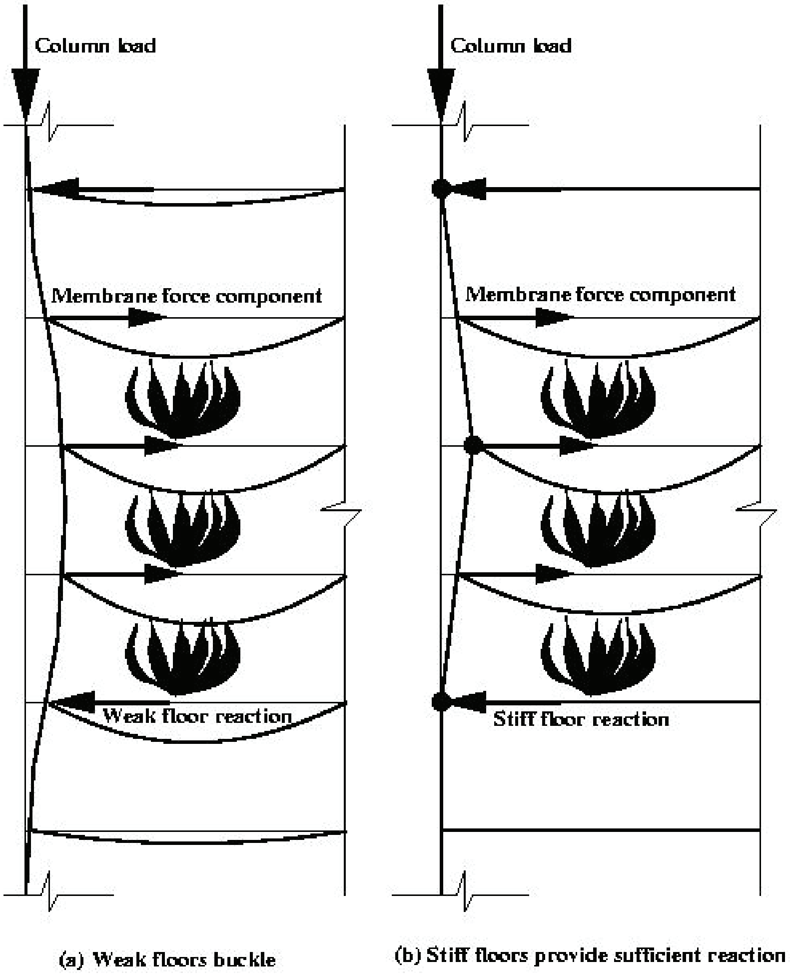
To provide early warning of the loss of structural integrity in a tall steel-frame composite structure subjected to a large fire, FireGrid will rely upon a range of structural models (both computational and analytical) that will be initiated upon the detection of fire and monitoring of its progress. One or more of the following strategies will be adopted depending upon the resources available to FireGrid for structural integrity assessment:

- ‘Matching’ of fire development information derived from sensors against a large enough space of computationally-generated predictions of fire scenario and associated structural responses, in order to facilitate rapid early forecasting (with possible use of Genetic Algorithms).

- ‘Modelling’ for structural integrity assessment in real-time based on monitored, simulated or forecast data. The choice of models will depend upon the computing resources available, ranging from simple analytical models to various sizes of detailed computational model; all will be setup before the event and will be initialised and updated using monitored data.

Large FEM models of structures in fire, e.g. ABAQUS, can be run efficiently by exploiting HPC resources and parallel processing; however these types of simulation are unlikely to be feasible for use in forecast mode (super-real-time) in the short term. Hence, simple models are also being developed (Lange *et al.* 2007), which are used to create a first level of structural integrity forecast capability as described below.

Figure 8 shows two possible failure scenarios for a tall building when subjected to multiple floor fires (Lange *et al.* 2007). Floors subjected to a prolonged fire invariably weaken and often undergo very large deflections, to the point where the main load-carrying mechanism changes from flexure to membrane or catenary action. This creates pull-in forces on the column (as shown, left) which require large supporting reactions at the adjacent non-fire floors to maintain the stability of the column. If the non-fire floors are unable to provide this resistance, and buckle, a 'weak floor failure' of the whole structure occurs. However if the adjacent floors are strong enough to provide the reaction, the column may fail in a mechanism formed by reaching full plastic moment at three points (as shown, right) leading to a 'strong floor failure'. A simple calculation procedure (Lange *et al.* 2007) can be exploited in assessing the structural integrity of the whole frame, as described in the numbered steps.



(a) Weak floors buckle
(b) Stiff floors provide sufficient reaction

Figure 8: Tall building failure modes in fire and a forecast scenario

1. Monitor fire at all floors adjacent to exterior columns
2. Forecast floor temperatures at appropriate intervals
3. Estimate structural temperatures
4. Determine floor and column deformation based on forecast
5. Estimate floor loading
6. Determine each floor's capacity to sustain loading in flexure, if insufficient, determine catenary capacity and consequent pull-in force
7. Determine reactions at adjacent floors and induced deformations
8. Determine capacity of adjacent floors to sustain reactions (while subjected to combined bending and axial force), if the capacity runs out return possible

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failure for the given forecast temperatures

9. If weak floor failure does not occur, check for combined bending and axial force capacity of column under the applied loading and return failure forecast if the 3-hinge mechanism is formed.

Further coupling strategies, based on advanced numerical modelling, are being studied for potential exploitation in the longer term, or for simpler scenarios. The most general approach is use of coupled CFD-FEM codes for detailed assessment of the response of a particular structure to a given, modelled fire. Coupling methodologies have been studied in the RFCS-funded FIRESTRUC project (Kumar *et al.* 2007) and project partners ANSYS-CFX have developed a software product which has a fully-coupled capability, the ANSYS MFX Multi-field™ Solver for fluid structure interaction. Also, for protected steel structures, a parallel project (Liang *et al.* 2007) has developed a generalised thermal analysis model (GeniSTELA) which gives CFD-based predictions of steel failure based on a number of variable input parameters, *e.g.* member specifications, the temperature-dependent properties of the protection materials and surface heat transfer parameters.

Fire-egress coupling

A number of fire-egress simulation tools are available, such as CRISP, which uses the Monte-Carlo method to explore the evolution of conditions with probability distribution functions defining each of the uncertain input parameters (Fraser-Mitchell & Pigott 1993). A novel approach to exploiting this type of tool is to replace some of the model inputs, which are typically based on assumed distributions of probabilities, by measurements, or parameters derived from measurements, then restarting the simulation, at intervals, using these updates of the real conditions. The input parameters ideally include both estimations of the fire conditions from simple sensor, and people movement, obtained via more advanced monitoring systems. Though the latter may not currently be very feasible under many real scenarios, the effect of such uncertainties can be studied by comparing the modelling results based on an assumed perfect knowledge of occupant behaviours to those obtainable when these are sampled to create more realistic inputs. In the first instance the coupling will be explored on the basis of pseudo data which is generated directly by the model itself, run in deterministic fashion, for a hypothetical scenario.

Though highly challenging, such integrated modelling tools will have many spin-off benefits, in addition to the super-real-time prediction of the emergency evolution and egress. One example of this is their potential use for cost benefit analysis on the measurement infrastructure, i.e. assessment of the added value consequent upon the types and spatial resolution of the sensors. By progressively reducing the level of information available to the simulation tool, the impact on the quality of the predictions can be assessed, in order to optimise their deployment, both in terms of their type, numbers and locations. These comparative studies will also reveal the true importance of monitoring the human behaviour, a particularly complex aspect of the problem and an area where there are many open research questions.

Ultimately, in the final application and live demonstrations of the FireGrid technologies, the simulated data will be replaced by real-time measurements from sensors. Recorded data, such as that obtained from the Dalmarnock fire tests, can also be used for the same purpose, the information being played back in real-time in a virtual representation of the experiment.

Wireless sensor networks

If FireGrid systems are targeted at large complex infrastructures, then a typical scenario could involve many thousands of sensors. These sensors would monitor the environment and ensure that essential information is delivered promptly. It is expected that the sensor network will also perform initial data validation and filtering to minimise data transfer and also reduce false alarms.

The number of sensors envisaged may preclude the use of conventional algorithms and demands a hierarchical architecture that deals with the various types of sensors (e.g. smoke, CO, temperature, etc), the different types and ranges of information, and the variable data rates. The data rates will be modest, typically updating on a 0.1-1s interval with a few kilobits per sensor. This hierarchical structure would work on several levels, *i.e.* on a routing level, on a location basis, and by sensor type, thus enabling the management of the large number of sensors and the data they will provide.

The reliability and durability of the sensors in a fire are essential to the success of this work and will require investigation. The survivability of a sensor implies some form of shielding from the environment which may have implications for the instrument sensitivity and the communications technology. The likelihood of sensors being destroyed suggests that the communications network will have to self-organize without prior knowledge of the network topology. It is not sensible to consider the conventional star topology (with strong centralised control) for such a network, as there would be a major risk of the system collapsing with the failure of single elements.

Traditionally, wired infrastructures, where all the sensors are physically connected, have been used in large-scale fire tests (e.g. Cardington), with data-logging equipment housed remotely. This was also true for Dalmarnock, where all the sensors were passive and were polled by a data-logger at a predetermined rate. Despite being a well-studied and mature technology, a significant issue with such systems is the challenge of effectively protecting the cabling, and the associated costs. Furthermore, data-loggers themselves are expensive and of finite capacity. Due to reasons such as these, there has in recent years been a lot of interest in replacing the traditional data logging systems with dense networks of wireless sensors. However, the combination of a sensor density and the frequent and fast sampling may present a significant burden to current wireless communication protocols. Since one of the main aims of the project is to provide an early fire detection capability, and a means of eliminating fires before they have really developed, high sampling rates are essential, even under normal operation conditions. With wireless systems, and the large numbers of sensors required, there are then severe practical constraints on maintenance. FireGrid addresses optimisation of such networks, including measures to reduce the amount of data to be transferred, making use of the correlations inherent in the fire measurements, *e.g.* gas-phase temperatures in upper layers or post-flashover fires (Tsertou *et al.* 2007). A current unknown in fire applications is the possible attenuation of the signal while travelling through the ionised products of combustion; this can be investigated in full-scale fire tests.

Grid

Grid-enabled distributed computing is vital to the success of this project. Grid technology supports the co-ordination of all remote computation and data resources. Each resource in a FireGrid system is accessed via a Web Service with a well-defined set of interfaces and behaviours, able to communicate in standard ways with the other resources using a mixture of communications protocols as required. These resources are co-ordinated by the C&C system which has been modified to use the appropriate Web Service protocols.

'Design mode' operation of FireGrid requires the integration of the fire modelling code, plans of the building, and the C&C system. The designers will use the system to run simulations of different types of fire in many parts of the building, evaluating their designs in the light of the predicted outcomes. Each run uses multiple fire models with a range of input parameters, to give statistical reports of the most likely outcomes.

Thus modelling of the different aspects of a fire involves the input, management and output of potentially very large quantities of information. The FireGrid system includes data management tools to handle the large number of simulation results. HPC job submission and control are implemented using the Globus Toolkit (Foster 2005) with remote access to distributed, heterogeneous databases of model input data using OGSA-DAI (Antonioletti *et al.* 2005).

A key part of the system is the interface between the numerical models and the decision support system. The decision support system expects input in the form of discrete events and information of interest, which it uses to generate options which might be explored for emergency response plans and to guide which simulations to run. For each type of fire model, an interpretation layer is required to analyse the results of the simulations so as to extract the information of interest.

The 'design mode' will also allow for the creation and storage of emergency response plans or components of them. These need to be indexed in a form usable by the C&C system, for example to select partial responses to its input events. A metadata system is being developed for describing these plans, enabling the system to find and load relevant response options for unfolding events.

The 'emergency response mode' brings the sensors and forecast capability into the mix. The forecast scenario presents unusual demands on HPC systems: it requires rapid access to significant resources at unpredictable times. It is unlikely that a single resource could be devoted to this application, as it would result in an expensive piece of hardware lying largely idle until required in an emergency situation. A more realistic approach is to be able to access such resources on-demand, recruiting existing HPC facilities at short notice. This will require these systems to support priority scheduling, displacing any mundane work currently executing. Most current HPC scheduling systems do not support this form of scheduling; rather, they optimise the maximum throughput of the resource (Andrieux *et al.* 2004). FireGrid will leverage work being done elsewhere on new workload schedulers and policies.

It is likely to be advantageous to be able to access a large number of resources for the forecast capability, both as a form of redundancy against failure and as a means to exploit multiple resources to execute successive forecast runs. This requires dynamic discovery of resources, using a grid registry system such as MDS (Zhang *et al.* 2003). An important function of the grid will be to allow escalation of the computer resources involved as the event increases in magnitude.

The other key demand made by the emergency response mode is that the sensor input must be routed to the simulations. FireGrid records all sensor information from a given building in a central database, which is then accessed as necessary by a range of Data Interpretation Units (DIU's). These DIU's range from relatively simple units that report the likely presence of a fire, to complex modelling units that run multiple linked forecast simulations. All of these access the data they require from the database. The intricacies of the sensor routing algorithms are hidden from the rest of the system, but the system can access the data stream from the sensors.

In a deployed system, the database and initial decision support system may be in a building-specific C&C system, which can then link to remote facilities if and when required. Alternatively, the database may be a remote facility. It can even be mirrored at multiple sites for robustness – a key quality of an emergency-response system. Similarly, there must be multiple routes for sensor data to be accessed outside the building, so that the loss of one such route does not prevent the overall system from functioning.

Thus the architecture demanded by the FireGrid system is fundamentally-distributed, heterogeneous and loosely coupled. It requires significant computational power to be made available on-demand, with little advance notice; it needs to couple multiple high-performance simulations with remote databases of maps and building structures; it needs to assimilate data from thousands of sources in a sensor-rich environment; and it needs to interactively communicate with building management and control systems and human beings – fire-fighters, for example – in hazardous, wireless environments. All of these are co-ordinated by the grid-enabled C&C system, which provides a platform that also allows access to the growing range of information resources, web services and remote expertise available through the internet.

Watertight mechanisms for authentication and authorisation are essential to FireGrid. A strong web of trust between the different components of the virtual environment is crucial to such a life-critical system. Grid technologies such as Globus provide highly secure proxy authentication mechanisms that can propagate the authority of the C&C system to enable the 'requisitioning' of significant – and expensive – computational and data resource at very short notice.

It is noted that a fully-deployed emergency response grid will pose particularly onerous security requirements. As an extreme example, consider an arson attack on a building protected by FireGrid. If the attackers are aware of the FireGrid installation, they could launch a co-ordinated cyber-attack to prevent the FireGrid system responding to the arson attempt. There is also a possibility that an installation will come to rely on FireGrid, thus weakening conventional response mechanisms, making the security issue vital in this context. This is beyond the scope of the current project.

HPC (High-Performance Computing)

FireGrid integrates several existing modelling packages and software tools. These will be enabled as grid components. Where necessary, sequential codes will be parallelised. All these components will be loosely coupled to represent all aspects of a fire scenario.

For the emergency response mode, these components will have to simulate the fire in super-real-time. This poses a significant computational challenge. A single serial CFD simulation of a typical compartment fire may not currently be possible in super-real-time and can generate large volumes of output data; this problem is severely compounded in cases where many alternative scenarios warrant investigation and for large and complex facilities, of the type where FireGrid stands to provide the greatest benefit, the problem clearly requires state-of-the-art HPC resources for super-real-time modelling. To achieve this goal a combination of algorithmic simplification and parallel computing is required.

The emergency response mode of FireGrid may not rely upon high-resolution fire modelling predictions of the entire event, which would be an unrealistic expectation. Instead, a hierarchy of modelling complexity is exploited and extrapolation is combined with continuous verification from the sensor data. This makes viable the use of simplified conceptual models in combination with advanced simulation tools, such as CFD and FEM. Complete simulations are executed for short time intervals, and continuous feeds of data are used to calibrate models that simplify the most computationally intensive areas of the calculation in real-time. This allows rapid extrapolation of the progress of the event for time-scales much larger than the fully computed periods. A key research topic is therefore to make efficient use of sensor data to steer and accelerate simulations in this way. In addition, simulations can be performed in parallel, discarding those that do not match the sensor input and replacing them with new simulations.

Command and Control

The Command and Control (C&C) task can be defined as the exercise of authority and direction over available resources towards the accomplishment of some objective. The standard application of C&C is found in military contexts, but the same concepts apply to civilian situations where there is a clear need to impose control and marshal resources. Fire-fighting is one such situation. Whilst the term ‘command and control’ is used in this paper, modern systems also refer to ‘command, control, communications and intelligence’ (C3I) and ‘command, control, communications, computers and intelligence’ (C4I) to emphasise the importance of situating these systems in their proper organisational and, increasingly, technological contexts, something that is of obvious importance for the success of the FireGrid project.

The C&C process consists of repeated cycles of a number of subtasks, namely: the collection of data from sensors and other sources; the analysis of these data and the current situation in general; the choice of a particular course of action to take; planning for the enactment of this action given the available resources; the direction of the resources to enact the plan; and finally, the assessment of the outcomes of the enacted plan. It should be emphasized that the goal of C&C systems is not to automate this entire process. In FireGrid, the first responses may well be automated – sprinkler systems, halon gas, evacuation signs, etc. – but when humans join the loop the role of the C&C system is to facilitate this cycle and support the human decision-maker. The C&C system is the 'glue' that holds a response organisation together.

In the FireGrid 'design mode', the C&C system will assimilate data from building maps and fire models and evaluate the suitability of automated responses. It will support 'what-if' exploration of possible scenarios, guided by the design team. This will provide valuable feedback on the building design. In 'training mode' the C&C system will use this multiplicity of potential emergency response scenarios, in conjunction with simulated agents, to support simulations and prepare potential responders for the likely emergency events.

In 'emergency response mode', the C&C system will be a bridge between grid services and emergency responders by assimilating incoming data of the current fire, by allowing the retrieval and presentation of appropriate maps and fire models from databases, by facilitating user interaction with the simulators by allowing appropriate queries to be posed, translating these into the requirements for specific simulation jobs and scheduling and initiating these jobs, and then presenting the results in an appropriate form, by assisting in the construction and elaboration of suitable response plans, and by allowing the communication of actions to emergency responders on the ground.

In common with a number of C&C systems in the past, this system draws upon Artificial Intelligence concepts, specifically knowledge-based and planning techniques. Much modern AI research is focused on providing support to human agents (and as such corresponds well with the objectives of C&C system builders). The impetus for this lies in an acknowledgement of the differing capabilities of humans and computers, and its aim is to engineer environments where these capabilities will complement each other to greatest effect.

The I–X research programme (Tate 2000) is typical of this type of modern AI project. Its overall aim is to create an enabling environment for mixed-initiative (i.e., involving both human and computer agents) activities. At the heart of the programme is a unifying upper ontology for a shared representation of a task, whatever the precise nature of the task or its domain may be. This conceptualisation, the <I-N-C-A> ontology (Tate 2003), is based on the notion of both the processes governing the task and the artefacts emerging from it being composed of abstract 'nodes', whose relationships are described by a set of constraints. Issues relating to the current nodes are cyclically generated and resolved so as to refine the set of nodes and their relationships and, in so doing, move the task forward. As well as encouraging a principled encapsulation of the task, the model also provides the basis for a systems architecture and communication framework, allowing the concrete realisation of I–X systems. The I–X approach and its supporting technologies provide the basis for the C&C component of the FireGrid system.

For a human user, the principal interface to the I–X technologies is a Process Panel (Tate *et al.* 2002). Process Panels present to users the current state of the collaboration from their individual perspectives, and allow them to decompose activities, refine elements of the plan, delegate issues, and invoke automated agents, all serving to move the overall task toward completion. Libraries of 'standard operating procedures' can be accessed to provide model plans for archetypal activities (such as 'best practice' responses to particular types of fire). In addition to this activity management engine, a panel gives its user access to domain-editing and planning tools, visualisations of the collaboration space and agent-relationship editors.

In addition, to fully realise the C&C aspect of FireGrid, it is necessary to engineer knowledge-based support layers to, for instance, abstract the raw sensor data into concepts meaningful to the responders (e.g., "the central stairwell is on fire") and interpret simulation results ("the ceiling of the central stairwell will collapse in 10-15 minutes') so as to provide 'intelligence' for decision-making. Another key aspect is the provision of suitable visualizations of this information, allowing for the most immediate communication of its content.

Applications in the Dalmarnock Fire Tests

Clearly a system such as FireGrid demands careful evaluation and assessment. A series of demonstrator experiments is being undertaken, beginning with the initial pairwise technology integrations outlined in Figure 2. These integrations are projects in their own right and will involve detailed testing. The demonstrators culminate in a well-instrumented full-scale test in a representative real-world fire scenario, intended to provide an example of the operation and potential of the FireGrid system. The Dalmarnock Fire Tests, the subject of this book, provided an opportunity to run this type of test in a realistic multi-storey building, permitting advance evaluation of various issues associated with the deployment and operation of the FireGrid system. Since the system itself was still under development, the role of the sensor-linked predictions was essentially substituted by a human 'fire science expert'.

Two parallel full-scale fires in a flat were run at Dalmarnock (Tests One and Two, see Chapters 3 and 4). The former were deliberately set up in order to be representative of possible real fire events, with the fire flat being furnished as a living room/office. Crucially, these experiments were run as parallel scenarios in order to investigate the role of intervention in mitigating these types of fire incident, as reported in Chapter 4. It is also important to note that even though there was only a single opportunity to run this type of fire in a real-world setting all of the recorded test data could potentially be used, in a virtual playback mode, to assess the performance of the whole FireGrid system under precisely the same set of conditions as existed in the real fires, supporting the 'research mode' deployment of FireGrid. The different aspects of the tests with particular relevance to FireGrid are now discussed in more detail.

Instrumentation

As reported elsewhere in Chapter 2, the tests were very well instrumented, with measurements of gas- and solid-phase temperature, total heat flux, gas velocity and optical density, together with different sorts of smoke detectors and a range digital imaging. Several hundred channels of data were logged in each of the fires, with the gas-phase thermocouple distribution, in particular, representing local conditions on a resolution comparable to a typical CFD grid; these were polled at a 10 Hz frequency, again comparable to the typical numerical timestep of CFD codes. About 25 GB of results data was obtained in total, of which less than 100 MB is from the data loggers, the rest being video records.

Of course, much of this instrumentation is specialist equipment for experimental fire testing and may not be typical of sensors currently found in buildings. In particular, the thermocouples for gas-phase temperature measurement are quite intrusive, being mounted on racks throughout the fire compartment, and could not be installed in this manner in normal occupied spaces. However, the aim was to comprehensively monitor the fire, and in order to test hypothetical scenarios with reduced or very sparse sensor provision the recorded data can be sampled in whatever manner is appropriate.

Command & control

As reported in the Chapters on the individual tests parallel experiments were conducted for two cases which were identical in all respects except for the ventilation control, *i.e.,* a freely-burning fire with no external control (Chapter 3) and one where human intervention was permitted for the purpose of mitigation of the incident (Chapter 4). In order to simulate the ultimate deployment of FireGrid, the latter case was implemented using human experts stationed in a control room remote from the event. All of the sensor values being recorded in the fire were at the disposal of these individuals, including several screens of information showing camera views and measured parameters from the fire compartments, cf. Figure 9. The role of these operators was to attempt to replicate the operation of the FireGrid system using their knowledge of the likely evolution of the incident to determine appropriate intervention and mitigation strategies. Control of the fire was accomplished solely by remote manipulation of the ventilation conditions via mechanisms for opening and closing the windows and doors leading to the main fire compartment, along with the front door of the apartment (Chapter 4).

Controlled Fire Test Two

The rate of development of the controlled fire was successfully 'managed' by a human operator. The temperature development curves presented in the controlled fire paper (Chapter 4) clearly show that the average temperature rise is suppressed throughout the duration of the test, and there is a noticeable delay in the timing of flashover. Whilst this in itself may not have been sufficient to make a big difference in the way the incident might have been handled in a real fire, it is indicative of what might be achieved if more advanced control strategies had been available, e.g. active suppression systems, in conjunction with early detection. Also, in many cases, any apparently small advantages which can be gained by early mitigation strategies may actually be of great benefit if the incident continues to escalate – they potentially buy crucial time for the fire and rescue services, giving them more scope for a successful operation once on the scene.

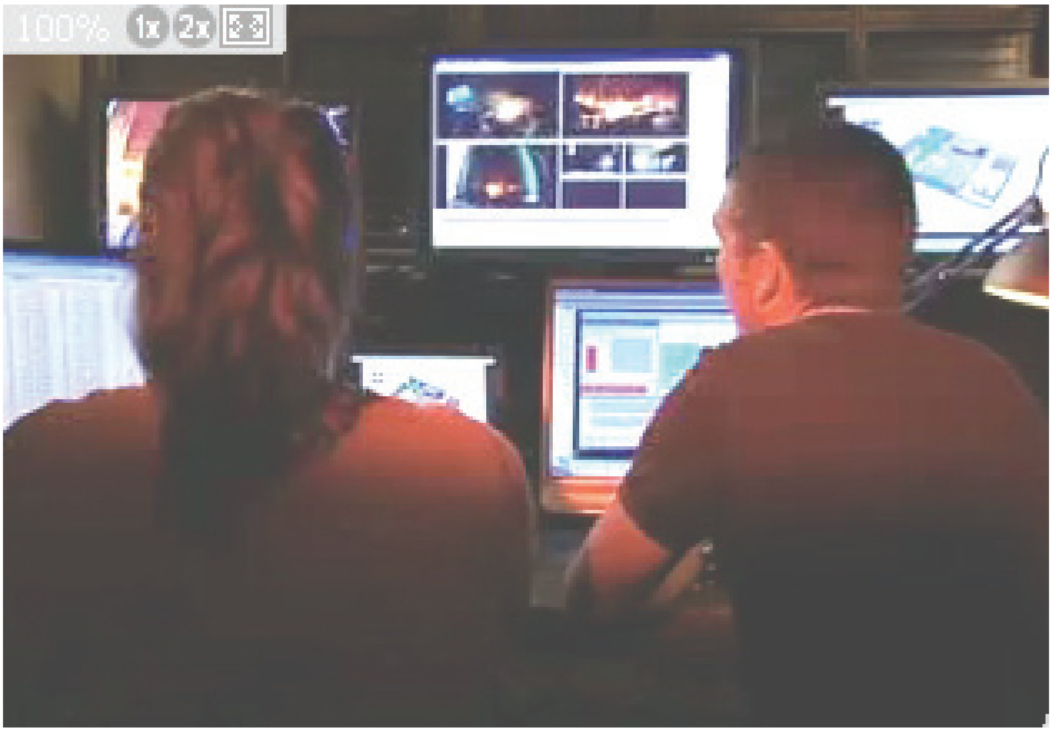

Figure 9: Control room and operators for controlled fire test

Another aspect highlighted in the attempts to control the fire is the fundamental limitations resultant from reliance on the intuition of human operators, however experienced they may be. Even in an incident of modest extent, such as the current fires, the sheer volume of data available to the experts quickly became overwhelming when the fire started to grow rapidly. Though more data was available, and given sufficient time for careful analysis, would undoubtedly have helped clarify the precise nature of the fire development at any point in time, the capacity of the human to deal with all of this information is in practice quickly exceeded. Moreover, the human overview of the monitored fire state is primarily concerned with the assessment of the *current* conditions, and any attempt to extrapolate from there to how the incident may evolve, for example involving structural response, becomes even more uncertain.

By contrast, the strength of simulation-based tools, with sensor linking, is that the constraints on the complexity of the cases which can be assessed are relatively limited. For example, the FireGrid system could potentially process measurements from a fire incident in large multi-compartmented buildings, or transport infrastructures with large open spaces, providing information on the current status and likely future hazards. If these conditions can reliably be assessed as being of 'low risk', then this may facilitate the active intervention of the fire services within the building; equally, where there are hazards which are not immediately apparent to the human operator, these can also be highlighted, potentially saving fire-fighter's lives and helping to guide egress priorities, e.g. through 'intelligent' signage. Compounding these benefits is the fact that all of this knowledge can be made available in advance, i.e. the fire service arrive at the scene of the emergency already well appraised of what might be going on inside a building, not having to rely purely on the limited information available via fire panel displays or assessment based only on the available visual cues.

Whilst highlighting the great potential of a system such as FireGrid, the Dalmarnock fires are also of assistance in engaging with the issues of information provision at C&C interfaces. It is clear that these need to be carefully designed in order to manage the supply of information to the human operators. Where appropriate, simple interventions, which are assessed as not needing the direct involvement of a human operator, can also be deployed automatically. This parallels what already exists in many buildings in terms of active fire suppression infrastructures, but provides the added value of the model-based interpretation of the fire incident.

Model Assessment

As reported elsewhere in Chapters 10 and 11, the predictions of the fire modelling software have been extensively evaluated against the recorded measurements from the sensors. This is undertaken both on the basis of *a priori* (blind) predictions, using a Round Robin study with a number of independent participants, and *a posteriori* validation simulations. Each aspect is very useful in establishing the capabilities and limitations of fire modelling tool for such applications. Whilst the *a priori* Round Robin study shows the often dominant influence of the decisions of the computer modeller, in agreement with earlier studies (Hakkarainen *et al.* 2007, Cox & Kumar 2002), the *a posteriori* study further reveals how challenging it is to simulate this type of incident, even when many aspects of the problem are well-characterised. The true behaviour of complex combustibles is very difficult to assess and quantify, particularly in the context of poorly defined and highly variable ventilation conditions. This was true despite the fact that there were no strong winds on the day of the Dalmarnock tests. Both these findings serve to highlight and stress the importance of appropriate and robust sensors for model correction and steering in order to obtain accurate representations of the way a fire incident may evolve, supporting the strategy adopted for FireGrid.

Conclusions

FireGrid is an ambitious and innovative project, seeking to develop the technology to support a new way of managing emergency response in the modern built environment. Specific novel aspects include the integration of diverse modelling tools for fire, structural response and egress, data assimilation strategies for leveraging these model

The Dalmarnock Fire Tests: Experiments and Modelling. Edited by G. Rein, C. Abecassis Empis and R. Carvel.

ISBN 978-0-9557497-0-4

predictions via real-time feeds of sensor data, exploitation of robust self-organising wireless sensor networks, high-speed processing using grid/HPC infrastructures with ‘on-demand’ access of remote resources, and application of intelligent C&C algorithms.

The Dalmarnock fire tests have provided a useful basis for the demonstration and discussion of these concepts and technologies, driving initial integration work and highlighting the potential benefits of such a system. Whilst it has been shown that active control of a fire may serve to mitigate its development, there are clearly severe practical constraints when relying purely on human operators. Whatever level of expertise they may have, provision of appropriate ‘intelligence’ for decision-making, derived from super-real-time simulations and made available via optimised C&C interfaces, will be crucial to practical deployment of the system. Moreover, due to the sheer complexity of the fire phenomena, even when confined to a single flat, it is apparent that the only way that meaningful *predictions* of the evolution of the incident can be achieved is by exploiting detailed knowledge of the current conditions obtained via robust sensor networks. These are the key technologies under development in FireGrid, which, when established, will have potential to transform emergency response.

Acknowledgements

The work reported in this paper has formed part of FireGrid, www.firegrid.org. This research has been funded by the Technology Strategy Board along with contributions from the other partners in FireGrid. At The University of Edinburgh, Wolfram Jahn undertook the review and analysis of data assimilation methods, Adam Cowlard led the upward flame spread test and modelling and Sung-Han Koo developed the conceptual models for fire-egress coupling, supported by Jeremy Fraser-Mitchell at BRE; Steve McLaughlin, Dave Laurenson and Athanasia Tsertou made a major contribution to the work in initiating and developing the studies of wireless sensor networks; Austin Tate and his research team have been responsible for the development of the I-X C&C technology; George Beckett, Gavin Pringle and Mark Bull, at EPCC, and Liangxiu Han, at NESC, supported the development of the grid architecture and demonstrators.

References

American Meteorological Society, Weather analysis and forecasting - an information statement of the American Meteorological Society, Bull. Amer. Meteor. Soc., vol. 88, 8 August 2007

Andrieux, A., Berry, D., Garibaldi, J., Jarvis, S., MacLaren, J., Ouelhadj, D. & Snelling, D., Open issues in grid scheduling, UK e-Science Report UKeS-2004-03, April 2004.

Antonioletti, M., Atkinson, M., Baxter, R., Borley, A., Chue Hong, N.P., Collins, B., Hardman, N., Hulme, A.C., Knox, A., Jackson, M., Krause, A., Laws, S., Magowan, J., Paton, N.W., Pearson, D., Sugden, T., Watson, P. & Westhead, M., The design and implementation of Grid database services in OGSA-DAI, Concurrency and Computation: Practice and Experience, vol. 17, pp. 357-376, 2005.

Berry, D., Usmani, A., Torero, JL., Tate, A., McLaughlin, S., Potter, S., Trew, A., Baxter, R., Bull, M. & Atkinson, M., FireGrid: Integrated emergency response and fire safety engineering for the future built environment, UK e-Science Programme All Hands Meeting (AHM-2005) , Nottingham, UK, 19-22 September 2005.

Cowlard, A., Auersperg, L., Richon, J.B., Rein, G., Welch, S., Usmani, A., & Torero, JL., Super real time prediction of upward flame spread, Proc. 5th Int. Sem. Fire & Explosion Hazards, Edinburgh, April 2007. [Also presented at the 5th Mediterranean Combustion Symposium, Tunisia, Sept. 2007.]

Cox, G. & Kumar, S., Modelling enclosure fires using CFD modelling, in DiNenno (ed.), SFPE handbook of fire protection engineering, 3rd ed., NFPA, Quincy, MA, 2002, pp. 3-194 to 3-218.

FireGrid Consortium, http://www.firegrid.org

Foster, I., A Globus Toolkit Primer, 2005.

Fraser-Mitchell, J.N. & Pigott, B.B., Modelling human behaviour in the fire risk assessment model CRISP 2, Proc. Int. Symp. CIB W14: Fire Safety Engineering, part 3, p. 1, 1993.

Globus Toolkit, http://www.globus.org/toolkit

Hakkarainen, T., Keski-Rahkonen, O. & Lindberg, L., CIB W14 Round Robin of code assessment: Design report of Scenario C, VTT Technical Research Centre of Finland, 1999.

Kumar, S., Miles, S. Welch, S., Vassart, O., Zhao, B., Lemaire, AD., Noordijk, LM., Fellinger, JHH. & Franssen, JM., FIRESTRUC - Integrating advanced three-dimensional modelling methodologies for predicting thermo-mechanical behaviour of steel and composite structures subjected to natural fires, RFS-PR-02110, publishable report, 2007.

Lange, D., Roben, C. & Usmani, A., Tall building collapse mechanisms initiated by fire, Part I: Analysis, Part II: Design Method, The Structural Engineer, submitted 2007.

Liang, H., Welch, S., Stratford, T. & Kinsella, EV., Development and validation of a generalised engineering methodology for thermal analysis of structural members in fire, Proc. 5th Int. Sem. Fire & Explosion Hazards, Edinburgh, UK, 23-27 April, 2007.

Michopoulos, J., Farhat, C., Houstis, E., Tsompanopoulou, P., Zhang, H. & Gullaud, T., Dynamic data driven methodologies for multiphysics system modeling and simulation", in *Lecture Notes in Computer Science*, Computational Science – ICCS 2005, Springer Berlin/Heidelberg, ISSN 0302-9743 (Print) 1611-3349 (Online), vol. 3515, pp. 616-623, 2005.

Tate, A., Intelligible AI planning, in Research and Development in Intelligent Systems XVII, Proc. ES2000, The Twentieth British Computer Society Special Group on

The Dalmarnock Fire Tests: Experiments and Modelling. Edited by G. Rein, C. Abecassis Empis and R. Carvel.
ISBN 978-0-9557497-0-4

Expert Systems International Conference on Knowledge Based Systems and Applied Artificial Intelligence, Cambridge, UK, December 2000.

Tate, A., <I-N-C-A>: an ontology for mixed-initiative synthesis tasks. Proc. Workshop on Mixed-Initiative Intelligent Systems (MIIS) at the International Joint Conference on Artificial Intelligence (IJCAI-03). Acapulco, Mexico, August 2003.

Tate, A., Dalton, J. & Stader, J., I-P2 - intelligent process panels to support coalition operations. In, Proceedings of the Second International Conference on Knowledge Systems for Coalition Operations (KSCO-2002). Toulouse, France, April 2002.

Tsertou, A., Upadhyay, R., Laurenson, D. & McLaughlin, S., Towards a tailored sensor network for fire emergency monitoring in large buildings. Proc. 1st IEEE International Conference on Wireless Rural and Emergency Communications, Rome, Sept. 2007.

Welch, S. & Marshall, NR., Development and validation of a comprehensive model for flame spread and toxic products in full-scale scenarios, Proc. 4th Int. Sem. on Fire & Explosion Hazards, Derry, September 8-12, 2003

Zhang, X., Freschl, J. & Schopf, J., A Performance Study of Monitoring and Information Services for Distributed Systems. Proc. HPDC, August 2003.

When citing chapters from this volume, the following reference style should be used:

Authors, Chapter no., Title, The Dalmarnock Fire Tests: Experiments and Modelling, Edited by G. Rein, C. Abecassis Empis and R. Carvel, Published by the School of Engineering and Electronics, University of Edinburgh, 2007. ISBN 978-0-9557497-0-4

Produced as part of the FIRESEAT symposium series:

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Published by the

SCHOOL *of* ENGINEERING *and* ELECTRONICS
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November 2007