The use of laboratory reconstruction in fire investigation

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Introduction

The complex, random and probabilistic nature of fire means that it is often impossible to fully determine how the fire developed and spread. There will be times when an appropriate and necessary understanding of a particular incident requires a laboratory reconstruction.

Reconstructions can be of particular value to a fire investigation. Those needing a reconstruction can range from the police or scenes of crime officers to insurance loss adjusters to public inquiry members. There are a wide range of questions that may need answering in a major fire investigation, starting from how did the fire start, through to what lessons can be learned from the incident. The objective of any reconstruction must be determined at the start since it may be a ‘test’, to measure material properties, an ‘experiment’, to find out what happened or check a specific hypothesis, or a ‘demonstration’, to illustrate what may have happened.

There are a large range of tests and experiments that can assist the fire investigator. Some tests will be to a defined Standard, others will be ad hoc. They include small-scale materials tests, medium-scale component tests, fire-resistance tests, large-scale assessment of interactions between items or components, full-scale re-creations, and demonstrations for inquiry teams or juries.

Before any reconstruction is attempted, the scale, size and the data required must be agreed. Other issues to consider include the level of realism appropriate, safety, costs and traceability of evidence. Because all fire incidents are different, all reconstructions are different, and so it is almost impossible to fully plan ahead. It is essential to have clear management and good communications on the project, and to keep full records and documentation, but reconstructions will always be expensive and will nearly always be resource limited, both in money and time. While it is sometimes possible to carry out small- to medium-scale ad hoc experiments on site, or at a fire brigade training facility, there are various specialist laboratories able to carry out these various tests and experiments. Full-scale reconstructions, in particular, need the services of a specialist laboratory.
It is always possible to learn lessons from real incidents; to seek to ensure that such events are less likely to re-occur and to identify the ‘near miss’ features. As well as assisting with the investigation of a particular incident, reconstructions supplement and underpin our existing knowledge base and ongoing research work and provide an essential link to events in the ‘real world’ to ensure the maximum confidence in future fire safety.

This chapter will discuss these various tests, experiments or demonstrations, and examples of how they have assisted fire investigations.

Why carry out a reconstruction?

There are a number of different organisations or parties that are involved in any fire investigation or inquiry.

Most fires will initially be investigated by fire brigade investigators. Where there has been loss of life or a crime suspected, the investigation will involve the police, scenes of crime officers, forensic scientists, the Coroner or Procurator Fiscal (for fatal accident inquiries in Scotland). If insurance fraud is suspected, or if a major insurance claim is made then the insurers, private investigators, specialist consultants and loss adjusters will be involved.

Once the incident comes to court then it will involve lawyers, the judge, barristers, and jurors. Expert witnesses and scientific advisors may be called upon. Others having an interest, either directly or through their legal representatives, might include the architect, the builder, the building owner, the occupiers, the maintenance engineers, victims, victims’ families, the accused and the accused’s families. Industrial or work place incidents will involve health and safety inspectors. If a major public inquiry is called, then a number of participants will be helping the inquiry members.

With regards to a particular incident, and in specific relation to any legal action, either criminal or civil, the issues that may be addressed could include the following.

- How did the fire start?
- Who caused it?
- Who is to blame?
- Was it as a result of an act of omission or commission?
- Has a crime been committed?
- Was the fire accidental, deliberate, malicious, arson, or fraudulent arson?
- Can the arsonist be identified?
- Who should pay? (Who else should pay?)
- Was a ‘material’ or ‘construction’ significant in the danger or losses from the fire? If so, who can be sued?
- Was the building design significant in the danger or losses from the fire? If so, who can be sued?
- Was the operation of the building, or management procedures, at fault?

Because a fire will destroy its own evidence there is frequently a need for conjecture and opinion based on inadequate facts and consequently there can often be disagreement between experts on what happened.

In addition, and especially in the case of multiple fatality or other high profile incidents, there may be an expectation that lessons will be learned that will go towards improving the law to seek to reduce the risk of similar incidents in the future (usually through regulations,
codes or standards). Learning lessons from an incident will often be one of the objectives of a Public Inquiry, a Coroner’s Court or a Fatal Accident Inquiry (Scotland). The issues addressed now might include the following.

- What lessons can be learned from this incident?
- Is it likely to happen again, or was it a freak event?
- Can it be prevented from happening again (or the risk significantly reduced)?
- Are there ‘political’ implications? (especially if government already knew about the particular problem)
- Are the current regulations (codes and standards) adequate?
- Were there unusual or unexpected features of the fire?
- Can it be shown how the fire developed?
- Does the ‘public’ expect a reconstruction?

In some cases, and especially in high-profile events, other organisations can have an interest. These include the media (particularly television) who often carry out their own investigation, or research bodies who have identified an unusual feature of the incident that demands further study. TV companies are often interested in pursuing a ‘pet’ theory or a perceived failing in the official processes. Scientists will be interested in using the incident to improve fire statistics and fire science for a whole range of disciplines. The incident represents an uninstrumented experiment from which lessons can be learned about physics, chemistry, engineering, management, biology, pathology, toxicology, human behaviour and psychology, within the context of fire.

All of the different people identified here will want to know the details of the fire but will all have a different knowledge of fire behaviour. Each and any of these (or their legal representatives) may require laboratory tests or a reconstruction to assist in their investigation.

**Purpose of the reconstruction**

**Issues that can be addressed by a reconstruction**

Not all of the issues that will be the subject of an investigation, trial or inquiry can be addressed in the laboratory. However, there are a large number of issues that can be addressed, examined or resolved by carrying out a reconstruction that include the following.

- How did the fire start?
- How did a particular item or collection of items burn?
- How or why did the fire-spread?
- How quickly did the fire-spread?
- Could it have spread this way or that?
- Did a particular material contribute?
- How hot did it get?
- How big in area did it get?
- How high did the heat release rate did it get?
- How long did it last?
- What did it look like?
- How smoky was it?
- How did the smoke spread?
How toxic was it?
How did the structure respond?
Did a material behave as would be expected?
Did a structural element behave as would be expected?
Did the building design, or a design feature, contribute?
Were there any unusual features of the fire?
Did the passive fire protection perform as required? (Passive fire protection includes fire protection coatings, dampers, and doors.)
Did the active systems perform as required? (Active systems include detectors, alarms and sprinkler systems.)
Did the fire resisting elements perform as required? (These include compartmentation and load-bearing elements.)

A single test or experiment may not answer all of these and a series of tests may be necessary. But it must be recognised that not all of the questions that need answering can be done so by a reconstruction. There may be key pieces of information missing so that the results of a reconstruction may add no value to the investigation. An example of this sort of problem is if timescales need to be established but the source of ignition has not been identified. In such a case whether the ignition source was smouldering or flaming will have to be assumed and the specific times in the test will be meaningless.

**The objectives of the reconstruction**

Specifying the objectives of a reconstruction is crucial and no reconstruction should be undertaken unless these are agreed with the client. While a laboratory will assist in the formulation of the objectives, it will be up to the client (i.e. the sponsor or funder of the project) to agree to the specification. It is therefore important for the laboratory to know who the client is, since they may be arranging the reconstruction through agents, such as expert consultants. If the agent has full delegated authority then this must be explicit and referenceable, since the objectives of the reconstruction could be subject to aggressive questioning in Court.

It may be the case that the client is a consortium, or a group of separate parties with a common interest, and a reconstruction can seek to address more than one objective. It is clearly in the best interests of all if a single reconstruction can serve in place of a number of them. Any reconstruction may lead to conclusions not related to the objectives, but (however valid) these must be considered a bonus. There are two ways to identify the objectives. Sometimes the client will come to the laboratory with a problem to solve and the scientist will tell the client whether a reconstruction will resolve the problem. Alternatively, the client will already know what is wanted and how to achieve it. It will sometimes be the case that a reconstruction to resolve a particular issue can, with some modification, be used to resolve other issues, or to provide an additional demonstration of other factors. It also needs to be recognised that the fire science community is quite small and that individuals working on the reconstruction will need to be aware of potential conflicts of interest.

**Types of test or reconstruction**

It is generally the case that there are four types of laboratory work that can assist a fire investigation.
Forensic laboratory tests

First, there are the ‘forensic’ scientific examinations, for example, for DNA samples, or the detection of accelerant residues. These are undertaken by forensic science laboratories, either government agencies or private forensic laboratories. This type of laboratory work is not discussed further here.

‘Standard’ tests

Second, there are ‘standard’ tests. These are tests, mostly bench-scale, which use a standardised method to determine or check specified material properties. Such tests are usually carried out according to the standard. There are a large number of fire performance standards, British, European, foreign or international, and the most common of these in the UK are given in Appendix A. Sometimes it is appropriate to modify a standard test to meet a specific objective, or to use a standard test method for a material for which that test is not intended. The test will then be considered ad hoc and the test report should state ‘...carried out using the method of standard test x’. These types of ‘standard’ test are discussed briefly later, since they can provide a very useful basis for a more elaborate reconstruction.

Experiments

Third are experiments. These are intended to answer specific questions, to gain new knowledge or to test a hypothesis. As discussed earlier, experiments may be required to find out what happened or how quickly it happened or check a specific theory, for example, to see if the fire could have grown to a particular size. Experiments can be of various sizes or scale, from small bench-top experiments to full-size reconstructions. It is the larger of these experiments that is the main subject here.

Demonstrations

Fourth are demonstrations. These are usually medium to large-scale reconstructions in which it is not anticipated that any new knowledge will be derived but are intended only to show what happens to a non-specialist audience, for example, an inquiry team or a jury. Demonstrations will often, fortuitously, lead to some new understanding. Demonstrations are also used for training fire investigators. Reconstruction demonstrations require much of the same planning as large-scale experiments, but usually with less instrumentation. They are also the subject of discussion here.

Designing the reconstruction

Primary issues

As mentioned previously, the first issue for a laboratory is to identify the client or the delegated agent of the client. The objectives of the work must then be identified and agreed. There will nearly always be constraints, of money or time or both, which will impose limits on what can be achieved. Financial, time and other controlling factors must be determined
and agreed early on. The extent and reliability of the existing knowledge needs to be defined, and assumptions, both those of the client and those of the laboratory (in order to carry out the reconstruction) must be agreed explicitly. The need for traceability of evidence must be specified if appropriate, and the type of reporting required must be defined.

With any project there needs to be regular discussions with the client, and, where possible, with other participants in the case. It is usually better to consult with other parties early on rather than risk the project falling in Court.

**Other planning issues**

There are a number of other issues that need to be agreed with the client before the design of the reconstruction commences. These include:

- The use of material from the actual incident. If this is evidence, especially crime scene evidence, how must it be stored, and for how long?
- Storage and physical security of data and other records and documentation. How long will the data and other records from the reconstruction need to be retained? Electronic security of data and other records and documentation. How long will the data and other records from the reconstruction need to be retained and will they be retrievable?
- Contingency and/or liability issues.
- Confidentiality.
- Physical security of the reconstruction (e.g. against media intrusion).
- Ownership of results and ‘publication’ policy.
- The use of computer models.
- Dealing with the media.

Many of these issues and the reconstruction design will be subject to regular discussion between the client, the client’s specialist advisors and the laboratory. It needs to be recognised that there might be times when the client’s requests are contrary to the advice of the laboratory. Such requests will need to be documented in the Report.

**Type**

It is possible to define the type of test or reconstruction only once the objectives have been specified. If ‘standard’ tests are needed, then these will be conducted according to the protocols that are in place as part of the laboratory accreditation for the particular test. The most commonly used ‘Standard’ fire tests in the UK are listed in Appendix A.

If an ad hoc test, reconstruction or demonstration is needed then it will be necessary to decide on the method to be adopted, what features or factors are to be demonstrated or investigated, the scale and size of the experiment and the type and quantity of data required. This will often be a balance between the ideal and the practical, determined by the competing factors of cost, time and quality. Sometimes an existing rig can be used for speed and cheapness, but if so, any factors that are then imposed upon the experiment must be carefully considered. Existing instrumentation can be utilised if it is appropriate.
The following types of experiment are available to help the investigation:

**Small-scale materials tests**

These are bench-scale ad hoc tests based on the standard tests and can provide information on the fire behaviour of a particular material, in isolation, such as a piece of furniture foam, or a wall covering. They can provide information on ignitability, combustibility, spread of flame properties or propensity to self-heating, for example.

**Medium-scale component tests**

These tests will use an existing test or research facility and involve whole items or components, such as an armchair, or stair carpet on a stairs or a piece of flooring. These tests can include calorimetry (measurement of heat release and smoke and combustion gas production under a, typically, 3 m by 3 m hood), fire resistance tests (on elements of construction up to around 3 m by 3 m, to examine structural stability and heat transmission), and irradiance tests (using a radiant panel, to examine ignition).

**Large-scale assessment of interactions between items or components**

These experiments can be part-scale, reduced-scale or full-scale reconstructions. Part-scale experiments involve only a selected element of the scene to be reconstructed, for example, the floor, walls and ceiling of one corner of a room (perhaps where the fire is thought to have started). Reduced-scale experiments involve a selected element of the scene to reconstructed, built smaller than the real scene. This can save on cost and time but the implications of the scaling effects, especially on timescales, will need to be carefully considered. Full-scale experiments involve the construction in the laboratory of a large and complete representative portion of the scene. The reconstruction will be fitted out with appropriate instrumentation.

**Location**

Once it has been decided that a reconstruction is needed, then the location for the experiment must be determined.

Exceptionally, an experiment can be carried out in the actual building of the incident, possibly in a similar location. This is only likely to be possible if the building is not badly damaged by the fire, and has the advantages of essentially identical materials and construction, which can avoid later controversies. Alternatively, a similar building might be located, for example, in a row of houses or on an industrial estate. This option is very seldom available in the UK but has been used successfully in the USA.

Relatively simple and small-scale ‘back yard’ experiments can be carried out on a nearby open space, perhaps the car park of the affected building, or using the fire brigade training facilities. Such experiments will have very limited instrumentation, if any.

In general, and particularly for major inquires, the facilities of a specialist fire laboratory will be called upon. Such laboratories will either use an existing rig, or construct a special rig, within a specially equipped laboratory or in the open in identified locations.

A number of specialist fire laboratories are listed in Appendix C. Any laboratory selected to carry out the ‘Standard’ fire tests should be accredited by UKAS (the United Kingdom Accreditation Service), or the equivalent national body, for that particular test.
**Realism**

The next step in the design process will be to determine how ‘realistic’ the reconstruction needs to be. This will in part depend upon the objective of the reconstruction, in part upon the importance of the parameters being assessed, and in part on limitations of cost and time. Issues to consider will include the following.

**Construction method**

Often the least important factor, provided the materials are realistic, the structure or the rig needs to be representative of the actual incident if issues such as collapse could be important. Rigs are typically constructed of timber with ceramic board, or from blockwork.

**Materials**

The materials, both of the rig construction and any furniture, furnishings or contents, must be carefully considered. Ideally, materials retrieved from the actual fire should be used. Alternatively, a materials audit (a review of the actual fire) needs to be carried out and documented. The materials then selected must be shown to be either identical with those in the incident, or of identical (or adequately similar) properties with regards to fire performance. Alternatively, it must be explicitly shown (and defensible in Court) that the particular materials were not significant in the incident. Materials used for the recreation must be appropriately conditioned (e.g. with regards to humidity).

**Dimensions**

The dimensions of the recreation will be determined from the objectives of the experiment. A small rig can be used if the early stages of ignition only are being examined. If fire-spread across a room is the issue, then the rig must be that size. As mentioned before, reduced-scale rigs can be built smaller than the real scene (particularly ceiling heights) but the implications of the scaling effects, especially on time scales, will need to be carefully considered. Radiation effects are difficult to scale.

**Details**

The need to attend to the details will also be determined from the objectives of the experiment. These will include ventilation, ambient conditions, humidity, temperature, wind, condition of the materials (in particular moisture content, but also surface damage, ageing, weathering, and for paints, curing), and physical details such as door cracks and wall lining fixings. As discussed next, these are often the subject of assumptions.

All of these issues need to be documented and included in the Report. It is usually of value for the laboratory scientist who is designing the recreation to see the incident fire scene, but this is not always possible.

**Assumptions**

In planning and designing a reconstruction, it is essential to identify and record all and any assumptions. This can be crucial in Court, and failure to do so can result in the entire project
being thrown out. It is necessary to beware of ‘hidden assumptions’ that is, where something is ‘taken for granted’ or ‘we always do it that way’, for example involving a component or element that no one has thought about. Again, the whole project can fail if a crucial and unconsidered assumption is identified by the other side in Court.

It is necessary for the client and the laboratory scientist to ensure that they have identified and documented all of the assumptions and to critically review the information sources and assumptions that are specified by the client.

Issues to consider include, for example, the layout and dimensions, including details such as door cracks and leakage paths, the materials, the provision of the materials, the ignition source and the environmental conditions. Particular problems arise where specific details are unknown and where a misjudged assumption can have a critical effect on the results of the experiment. As stated earlier, it is usually of value for the laboratory scientist who is designing the recreation to see the incident fire scene, but this is not always possible.

**Detailed design**

The detailed design of the construction can only commence once the above-mentioned issues have been agreed with the client. These details will then include the following.

- The size and scale of the reconstruction. Will it be small, medium, reduced, large- or full-scale? The size and scale need to be representative or have an established and documented relationship to the real incident.
- The materials of which the rig will be made. There is a need to consider the type, thermal properties, conditioning and curing of these materials. They need to be representative of the real incident.
- The contents, furniture, furnishings or other items, that will go into the rig. Will they need to be specially conditioned or treated to be representative of the real incident?
- The use of actual materials and contents from the incident. If so, how will they be obtained? What condition or age will they be? Will they be traceable? What special treatment or conditioning will be needed?
- The need for any structural elements to have loading, either static and/or dynamic. How will this be determined?
- The ventilation conditions within the reconstruction. These need to be representative of the real incident, but how will this be determined?
- The ambient conditions (humidity, temperature, wind) within the reconstruction. These need to be representative of the real incident, but, again, how will this be determined?
- The duration of the fire. In many cases, the fire will be allowed to burn to completion, but, particularly for large reconstructions, some limits of time or other termination criteria will need to be agreed.
- Audit trails and traceability of evidence. These will need to be determined and agreed.

The ignition source to be used needs to be determined from the incident or else agreed with the client as an assumption. The type and size of the ignition source will significantly affect the timescales of the recreation. Failing any useful alternative, a ‘standard’ ignition source, such as a standard crib [1] can be used.

In most cases, there will always be some residual doubt regarding the details of the design of the reconstruction and the validity or soundness of any assumptions. It will be a matter of
judgement as to whether these doubts need be critical to the project, but it needs to be recognised that there will be times when the uncertainties regarding the incident make any reconstruction pointless. It is therefore best if all relevant parties agree with the proposed experiment in all its details. Sometimes an invalid assumption or faulty information from the incident only becomes apparent during or after the reconstruction fire. In such circumstances the possibility of additional reconstructions may need to be considered, but in all cases the interpretation of the results of the reconstruction will require a degree of expert judgement. It is generally the case that it is best to start with small tests and work up towards a large test or experiment.

Reproducibility

An issue which affects all large-scale fire research is that of the number of fire experiments. For fire investigation reconstruction, experiments or demonstrations, a single fire is often sufficient. However, if the effect of a particular parameter is being examined, for example, the quantity of accelerant needed, then a number of fire experiments may be needed, each using a different quantity. As discussed elsewhere, the number of experiments will in part be constrained by cost and time. But often it is possible to carry out smaller-scale trials to examine a range of factors before carrying out a single large-scale reconstruction.

The complex, random and probabilistic nature of fire means that it is often impossible to be fully satisfied that the reconstruction has adequately recreated the events at the actual incident. However, given that there will always be some assumptions inherent in any reconstruction, additional fires will not necessarily resolve the problem.

Instrumentation

The instrumentation in any reconstruction can be a significant cost in equipment, installation and analysis. Clearly sufficient instrumentation will be needed to satisfy the objectives of the project, but where this is limited due to resources the decision process needs to be documented. There are a number of parameters that can be measured during a fire reconstruction which are given here.

Temperature

Temperature is most simply measured using thermocouples. These devices depend upon the voltage produced where two different metals are in contact and need little calibration. They can be made quite cheaply from rolls of the appropriate wire, by welding or silver-soldering, of a thickness and metal type appropriate to the anticipated fire severity. Stainless-steel sheathed thermocouples are more expensive but are usually more robust. A ‘cold-junction’ is required to give an accurate reading, but this is nowadays almost always incorporated in the data logger. Measurements will be in degrees (Centigrade) and be continuous (subject to logging rate). Specialist help may be needed.

Heat flux

Heat flux (or heat flux density) is measured using off-the-shelf heat flux meters, which are moderately expensive. They are (usually) water-cooled devices, about 25 mm in diameter.
that measure the temperature difference across a small metal plate. They require careful calibration before use, and need a water supply. Results will usually be in kilowatts per square metre (kW/m²), and be continuous (subject to logging rate).

**Mass loss**

Mass loss is a means of estimating heat production. The mass of a selected item can be recorded using load-cells. The load cells must be calibrated and need careful protection from the fire. If the calorific value of the selected item is known, and the combustion efficiency estimated, then the heat production can be derived. However, in real fires the items involved usually comprise a mixture of materials, and so this technique is now seldom used. The following technique is now preferred. The mass measurement can be continuous (subject to logging rate).

**Heat release rate and total heat release**

These can be measured using oxygen-depletion calorimetry. This involves the use of a large hood and fan, positioned over the reconstruction, to collect all of the fire gasses. The gasses travel down a duct in which instruments measure temperature, velocity (hence mass-flow rate) and oxygen concentration. The mass of oxygen consumed by the fire can be derived and, via now well-established relationships, the heat release rate can be calculated. The measurement will usually be in Watts, kilowatts or, for large fires, Megawatts, and be continuous (subject to logging rate). By integrating the heat release rate over the duration of the fire, the total heat release can be derived (Joules). A number of specialist laboratories have such hoods. The largest in the UK are those at FRS, Garston (9 m by 9 m) and at the University of Ulster. The system must be calibrated prior to the reconstruction.

**Gas composition (and toxicity)**

A number of different gas species can be measured during a recreation, usually via a tube and pump. Some of these can be measured using online analysers, which can be continuous (subject to logging rate), and include:

- carbon monoxide
- carbon dioxide
- oxygen
- nitrogen dioxide
- nitric oxide
- hydrocarbons.

Others require the gasses to be collected in a flask (called a bubbler) containing an appropriate liquid. These are analysed later, by gas chromatography or mass spectrometry. These measurements will not therefore be continuous over the duration of the fire, but by using a number of bubblers, each running for a selected time period, it is possible to examine the different stages of the fire. Gasses that can be recorded this way include:

- hydrogen chloride
- hydrogen cyanide
- hydrogen fluoride
- hydrogen bromide
- sulphur dioxide.

Gas concentration measurement requires carefully calibrated equipment, and analysis, and is a heavy user of resources.

**Smoke density**

Smoke density can be measured at selected locations within a reconstruction using optical devices. These comprise a light source and a receiver, rigidly fixed a specified distance apart. The presence of smoke is recorded by a reduction in the receiver signal. The devices need calibration prior to the fire but give a continuous recording. The measurement will be in optical density per meter, or visibility (in m). Smoke detectors (ionisation or optical) can be used to identify the release of smoke, but these will not give a calibrated measurement.

**Smoke production**

Smoke production can be measured as part of the measurement of heat release (see Heat release rate). The optical density of the smoke within the duct is recorded and can be converted to a total quantity of smoke over the duration of the fire. The measurement will be in m². Alternatively, the mass of smoke can be estimated by gravimetric means; smoke particulates are collected on a filter and weighed.

**Deflection/stress**

Deflection is measured using displacement transducers. Stress can be determined for selected structural elements using strain gauges. These small devices depend upon a change of electrical resistance as the device changes shape.

**Visual**

Visual recording of the reconstruction will nearly always be carried out, nowadays using video equipment and stills photography. Video records are used to estimate fire growth, flame lengths, fire spread, and the response of items. Infrared photography or video may also be used. Sacrificial video cameras may be used in specific locations. Care needs to be taken with video since the recordings will often be used in Court and a ‘burnt-in’ time code may be required.

**Factors**

Planning for the instrumentation of the reconstruction will need to consider a number of factors, which include the following.

- Number of sampling points, number of sensors.
- Location of sensors/sampling points.
- Computer analysis (additional sensors, or different locations, may be needed).
- Duplication of systems.
- Protection of equipment and instruments from the fire.
- Sampling rate(s).
- Data format.
- Data security (including electronic security), long-term data security.
- Accuracy, sensitivity, calibration.
- Data logging, processing and analysis.
- Observations locations.
- Video cameras, stills photography; format, number.
- Physical security of recordings (tapes, discs, etc.).

**Safety**

Fire experiments, by their very nature, involve some dangers to personnel. Most specialist fire laboratories will have well-established safety procedures that will be called upon. These dangers will include flames and heat, particulate smoke (which can obscure vision), and combustion gases (which can be irritant and/or toxic). In addition, within the test rig, there can be risks from chemicals, toxic materials, electricity, structural collapse and explosion. Working within the laboratory entails risks from impact, drops, trips and falls, vehicle movements, etc. It is also necessary to be aware of, and mitigate, any environmental risks, from toxic materials, smoke or polluted water run-off.

The test rig should be designed to minimise risks and be able to be constructed safely. Overhangs and trip hazards should be avoided, but may be essential if part of the re-created layout. Electrical safety must be considered, especially, as is usual, water will be used to extinguish the fire on completion or if needed for safety. Bunds and reservoirs should be provided for fuel spillage and/or water run-off. Provision must be arranged for the safe disposal of liquid and material waste. The potential toxicity of these materials after a fire may require the services of specialist waste contractors.

A safety plan needs to be developed early in the project and integral to the experiment design. The safety plan will need to include a risk analysis and a description of how the risks are to be managed. The plan will need to consider the safety of observers and visitors, communications, access/egress, safety routes, places of safety, evacuation criteria and procedures, first-aid and first-aid rooms. Again, where observers and visitors will be present, the test rig will need to be cordoned with barriers and good signage. Sirens, klaxons or a public address system may be needed to communicate with large numbers of visitors. If large quantities of smoke are anticipated then direct viewing of the fire may not be acceptable and a video link to a safe observation room may be needed.

A well-defined safety team will be needed, with formal responsibilities and powers. There must be clearly identified tasks and roles. For larger experimental fires, the local fire service may be employed for firefighting and clear lines of communication and command will be established before the test date, with agreed safety protocols. Similarly, a first-aider may be needed in attendance.

On the day of the test, the Safety Officer will need to provide all participants with the safety protocol and give a safety briefing, describing the command structure and procedures. Agreeing to abide by the instructions of the Safety Officer will be a condition of attendance.
Termination criteria (for the fire) must be set. Although the experiment should be designed to minimise risks, appropriate safety equipment must be available to the personnel. These may include overalls, safety boots, hard hats, safety glasses, gloves, gas monitors (usually CO), additional lighting and if appropriate, respirators or breathing apparatus. First-aid facilities should be identified.

The provision of appropriate safety arrangements for a large-scale fire experiment can be a significant added cost to the project. Despite the best planning, there will always be some residual risks and these must be proportionate to the importance of the project.

**Conducting the reconstruction**

*Personnel*

The reconstruction will involve a large number of people and tasks. These might include:

- Officer-in charge
- Experimental staff
- Instrumentation (logging) staff
- Technical observers
- Safety Officer
- First- aider
- Steward (to look after visitors)
- Laboratory Audio Visual Crew
- Client’s Audio Visual Crew
- Fire Brigade
- Clients
- Guests
- Catering staff.

Guests at the recreation will be at the discretion of the client and might include the judge, jury, barristers, and experts from the various teams. Special arrangements are sometimes needed where a large number of guests are expected, including catering and washrooms.

**Schedule**

The schedule for any reconstruction may start weeks before the actual fire experiments. As well as resolving and organising the various design and planning issues as discussed before there will be a number of other tasks that will need to be programmed. These include:

- co-ordination with other users of the laboratory;
- organising or subcontracting construction of the rig;
- purchase of consumables;
- storage of materials, especially fuels;
- identifying and resolving any environmental issues;
- rig construction;
- supplementary construction and installation (e.g. bunds, ventilation systems);
• obtaining materials, furniture, etc. and conditioning;
• calibration of instruments;
• fitting instruments and data logging;
• fitting of ignition system and back-ups;
• commissioning rig, equipment and instruments;
• liaison with fire brigade;
• briefing team members;
• planning for clearing up after the fire, hiring skips, etc. and contracting specialist waste removal companies.

For the planned day of the fire experiment all attendees need to be provided with a programme in advance. The fire should be started only when everything is ready, so all attendees need to be made aware that precise scheduling is not possible. Once alight, it is seldom possible to deviate from the agreed schedule. All visitors need to be made aware that there can be considerable waiting time, often in an, initially, very cold laboratory.

Clients, visitors and guests will normally wish to inspect the reconstruction and care needs to be taken since many will not have previous experience of fire experiments. ‘Guided tours’ may need to be arranged. As well as safety considerations, there is a need to avoid damage to instrumentation.

All those attending, including laboratory staff, should be given a safety briefing, which will include identification of escape routes. Clocks and stopwatches should be synchronised.

Once observers are in place, a countdown can commence and logging, recording and video equipment can be started. At the planned time-point the fire can be started, either manually (e.g. with a lighted taper), or by an electrical device. Ignition is not always successful and a second start can be required. The time of restart will be recorded.

If the termination criteria are achieved, the fire will be extinguished. Alternatively, it will be left to burn out. Loggers and recorders may be switched off or may be left to run on. Clients and guests will wish to review the aftermath of the reconstruction. However, it is seldom possible to re-examine the reconstruction to assess damage until the rig has cooled and the smoke dispersed, which may take from an hour to a day. Safety protocols must be followed.

Until deemed otherwise, the site should be treated like a crime scene. Photographs will be taken and, where necessary, samples will be logged and removed. Instruments will be extracted.

The remains of the reconstruction will then need to be disposed of in accordance with the previously agreed procedures.

Results will then need to be processed and analysed. This may take some days (or weeks) depending upon the complexity of the experiment.

**Reporting**

The Report of the reconstruction, including photographs and supplemented by any video recording, will be the output of the project, and is very likely to be presented in Court. It therefore needs to be written with this in mind. This document will usually be written by the laboratory scientist and, subject to the requirements agreed with the client, may be a report.
of the results, or may include deductions and conclusions. Contrary to scientific practise, it is often better for the report to have a single author, even when a project team has been involved, since any of the named authors may be called into Court.

In general, the report should conform to normal good practice for expert evidence and will need to include:

- An introduction, including identification of the Client
- Background
- Instructions from the Client and purpose
- Appropriate declarations and statements
- Prior information
- Assumptions
- The reconstruction design, including geometry, materials, and issues of traceability
- Ignition source
- Instrumentation
- Results and observations
- Analysis
- The use of computer models, results, etc.
- Discussion, including deductions, if required
- Conclusions
- Acknowledgements, including the project team
- References
- Photographs.

It is essential that the laboratory have a quality and checking protocol to minimise the risk of typographical or other errors.

Often the findings from a reconstruction have wider scientific value. The results of the project will be owned by the Client and publication of the Report will be at the discretion of the Client. Courts of Inquiry will usually wish to publish. Once a report has been presented to the Court it is effectively in the public domain, but the cost of publication will be an issue. The laboratory scientist may be required to present the Report in Court. The Report can then be supplemented with the video record of the reconstruction.

**Costs**

It will have been seen from the discussions here that full-scale reconstructions do not come cheap. Bench-scale and ‘standard’ tests are much cheaper, but often can only provide some of the information needed in an investigation. Clients will naturally be seeking ‘value for money’, but an over-simplified experiment can be worse than useless since it can undermine the credibility of the Client.

The costs of the project will include:

- design, customer meetings, and staff;
- primary structure, construction, laboratory space (floor space rental) and facilities;
- storage and conditioning facilities;
- materials, fuel, the contents and furnishings;
- equipment, instruments, calibration, means to protect the instruments;
- audiovisual (stills camera and video cameras);
- the Fire Brigade and other safety requirements;
- clearing up afterwards, hire of skips and/or specialist waste removal companies;
- storage of evidence, storage of data (especially for an extended duration or under special conditions);
- travel and catering;
- data analysis and producing report;
- video editing;
- contingency and liability considerations;
- environmental protection issues;
- confidentiality, secrecy, physical security;
- some cost allowance for the laboratory scientist to give evidence in court. However, this is often treated as a separate issue.

It follows that all of these issues must be considered and agreed with the client at the start of the project.

**Case studies**

The following selected case studies are intended to illustrate the value of recreations, at the different scales as discussed before.

**Stardust Disco (Dublin), February 1981**

Following a series of small-scale tests, a full-scale reconstruction was carried out of the Stardust Disco (Dublin) fire [2]. This required a very large rig, clad with carpet tiles and fitted with tiered seating of the same type as in the incident. The fire was started at the rear of the set-up. The test demonstrated the speed and severity of the ensuing flashover fire.

**Windsor Castle, November 1992**

A medium-scale test was carried out to examine the fire development of the curtain in the Windsor Castle fire [3]. The fire was understood to have been caused by a hot halogen spotlight. Curtain of a type similar to that in the fire was set up on a gantry in the laboratory. The test was to show how quickly, and how, the fire would spread up the curtain.

**Dumfries House Fire, February 1995**

This project required an assessment of the contribution from the carpet to a fatal fire in domestic premises. An existing test room was used and fitted with carpet identical to that in the fire, and an armchair from the incident house. The fire was started on the armchair. The test showed how the carpet became involved in the fire under the heat from the chair [4].

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**Computer models for the fire investigator**

Computer models are increasingly appearing in Court and are being used as an adjunct or alternative to physical reconstructions. The fire investigator now needs to have familiarity with computer models, both to assist their own work, but also so that he/she might respond effectively to the results from models presented by other parties.

Currently, such models include the following.

- ‘Calculator’ packages, which link established equations.
- Zone models, to calculate smoke and gas movement in simplified conditions.
- Computational Fluid Dynamics (CFD) (Field models) to calculate smoke and gas movement in complex conditions. Fire-specific CFD models are available.
- Structural models, to calculate the loads and distribution of loads in the building structure when selected elements are heated by the fire. Some such models use finite element analytical techniques.
- Radiation models, to calculate the heat flux from a flame to a complex geometry.
- Sprinkler models, to estimate the response of a sprinkler head.
- Risk models, to estimate the numbers of injuries or deaths in a building under a very large number of different potential conditions. Some such models use ‘Monte Carlo’ sampling methods.
- Evacuation or egress models, to calculate times to empty a building, or the distributions of people leaving a building. Current models can include a variety of behavioural responses.

Some investigators use virtual reality visualisations, but by themselves these are only a means to providing a three-dimensional, moving and time-sequenced diagram, ‘drawn’ by the scientist, and extreme care must be taken in their use since they do not ‘predict’ an outcome. Such models are, however, now being linked to some of the above-mentioned computational models to assist in the presentation of the outputs. In these cases it must be clear what is predicted by the model, and what is drawn.

Very few fire investigators currently use computer models in their work and CFD models in particular need skilled users. A few models have been specifically developed by forensic scientists, fire investigators or fire investigation institutes, mostly outside of the UK.

While computer models are being developed for a very wide range of fire-related scientific issues, those of concern here are the models used to calculate and predict the spread of heat and smoke and are of the most value to the fire investigator since they can be used to assist the investigator to determine the speed of smoke spread or the temperatures as a result of a particular fire.

**Fire growth and spread**

Before a full theoretical model of fire can be constructed, a proper understanding is required of the complex and interacting mechanisms involved. The very strong coupling between the fire source and its enclosing structure makes fire a particularly complex problem to analyse. However, theoretical models of varying levels of complexity have now been developed which, with the aid of the computer, can be brought together to begin to describe realistically these phenomena. Such theoretical models have now advanced to the point where they
are used with some confidence to predict how the hot smoke and gases produced by a proscribed fire source will be dispersed throughout a building.

A complete treatment of the growth and spread of flame under realistic conditions, where complex arrangements of furnishings and building linings are involved, is not yet within the compass of their capabilities. But simplified analyses do permit an assessment of fire growth and spread to be made. To appreciate the types of computer model that are currently available it is necessary to understand at least broadly, differences in approach adopted by the various models.

Theoretical computer models that simulate the heat and mass transfer processes associated with a compartment fire, fall broadly into one of two categories. These are commonly referred to as models of either the zone or CFD type. The essential difference is in the way they treat the movement of the products of combustion within the building envelope and their respective reliance on experimental information.

Both types of model can predict gas temperatures resulting from a specified fire in a domestic-size room and both give broadly similar results. The field model predictions are much more detailed but, more importantly, are able to show detail such as a clear deflection of the plume caused by the fire-induced wind flowing through the doorway opening. The zonal model does not do this, unless it has been assumed a priori.

It is also necessary to differentiate between deterministic models and probabilistic models. The models described here are deterministic. Probabilistic models tend to have much simpler calculations but a very large number of simulations are conducted.

Zone modelling

Computer zone models are closely related to well-established traditional methods for the treatment of smoke movement, which were initiated before the widespread availability of the modern computer. They rely on a number of simplifying assumptions concerning the physics of smoke movement suggested by experimental observation of fires in compartments.

The availability of the modern computer has allowed this simplified approach to develop further to allow examination of growing fires and to include many more of the relevant influences such as heat loss to the surrounding structure and radiant ignition of remote objects.

In addition to permitting full enclosure fire simulations, the computer now offers easy access to some of the more simple semi-empirical zonal relationships that can be found in engineering guides and handbooks. Because of the ease with which these calculations can be repeated many times over, they are particularly valuable for undertaking preliminary scoping studies. But the zonal philosophy has limited general use because it is dependent on assumptions of how the products of combustion will behave.

A zone model may be specific to a particular problem and cannot be used for other applications.

CFD modelling

CFD modelling represents a break with the traditional approach used in zone modelling. Making essentially no assumptions about the physics of smoke movement, it exploits the techniques of CFD to deduce how, and at what rate, smoke would fill an enclosure. It does
this by avoiding resort, as far as is currently possible, to experimental correlations and
returning to first principles to solve the basic laws of physics for fluid flow. As a conse-
quence, this type of model is of universal applicability. For this approach, the computer is
the enabling technology; without it, the technique could not have developed because it
involves the solution of mathematical equations for every step forward that the simulation
makes. This is why the zonal type of approach, conceived before this capability had been
realised, had of necessity to resort to simplifying assumptions.

The difference between the two types of model is usually only of secondary importance
when applied to small compartments but can become very significant in large ones. This is
because the zonal method assumes that smoke fills an enclosure from the ceiling down.
Fires in tall enclosures, such as atria, may not necessarily behave in this way if, for exam-
ple, ambient conditions ensure a sizeable temperature gradient between floor and ceiling
before the occurrence of fire. In large area enclosures, smoke may not remain in a buoyant
layer; it may cool and mix with the lower ambient air before it can reach the outer bounds
of the enclosure. It may also be necessary to simulate the conditions before the fire started.

Simulations using field models are able to predict, without prior judgement, the behav-
ior of smoke flow from a specified fire and to permit smoke control strategies for such
circumstances to be assessed using the computer. Like their zonal counterparts, these
models allow comparisons to be made between the developing hazard and the time available
for safe escape of the occupants.

Models of this kind, being rather more complex and demanding of computer power than
their zonal counterparts, are still somewhat restricted to specialist users. Change is, however,
taking place as computer power becomes progressively cheaper and simulation models are
restructured to admit their use by fire safety practitioners.

Both types of computer model can provide information on when automatic detectors
or sprinklers are likely to operate and on the degree of heating of structural elements,
flammable contents and of occupants effecting their escape.

The decision whether to employ zone or field modelling depends upon the particular
application. Zone modelling will be cheaper but the assumption on which it is based may
not be applicable when used, for example, in the design of smoke control for compartments
of large volume. Similarly, when designing for early fire detection in compartments of any
size, where the energy released by the fire is still comparable with heat associated with
ambient air movements, field modelling becomes essential.

What theoretical modelling is not yet able to provide, in any rigorous sense, is a prediction
of fire size or growth rate for the generality of flammable materials likely to be found in
buildings.

Instead, rates of release of fuel volatiles, steady or growing with time, must be provided
as input data to the models. These can be determined for a particular fire load using exper-
imental data, fire statistics, expert judgement or a combination of all three.

Method

CFD (field) models involve setting up a large number of cells to represent the space to be
modelled. These cells will form a grid; in some models the geometry will be fitted onto an
existing grid, in others the grid will be constructed specifically around the geometry. The
computer then solves the equations that determine the flow, velocity and temperature, of the
gasses entering and leaving each cell, and, since the flow out of one cell will be the flow in
to the next, a very large number of iterations are needed to derive a solution.

Most fire simulation models have been developed so that they can be used as part of the
building design process. However, they may also be used to seek to reproduce real fire
incidents (e.g. the Kings Cross fire [5,6]). This is done systematically when validating the
models. Experiments are designed and instrumented to demonstrate that particular features
of the model function correctly and provide an indication of the models’ accuracy. Material
properties in the experiment are known and most importantly the fire heat release rate can
be measured for use in the models. If the models are used to investigate real fires then much
of the key input data has to be deduced from the scene of the incident and from reports of
witnesses. Estimation of the fire’s heat release rate may have to be drawn on a reconstruc-
tion of the fire or data from experimental fires using similar materials and configurations
(e.g. the NIST worldwide website includes a number of heat release rate curves for burning
items such as pieces of furniture).

To investigate a real fire incident the fire engineer needs to select an appropriate model
or models, know enough about the design and material properties, and estimate the relevant
heat release rate curve. This may result in having to run a number of simulations to resolve
‘What if…?’ questions by comparing the simulation results with known events during the
fire. Selection of an ‘appropriate’ model requires knowledge of the model’s assumptions and
limitations as well as its functionality.

Models used

Computer models that have been used to examine fires in buildings, post hoc, include the
following.

- JASMINE [7] (Analysis of Smoke Movement In Enclosures) a CFD developed for fire
  applications;
- CFAST [8] a multi-compartment zone model;
- CRISP [9] (Computation of Risk Indices by Simulation Procedures) a multi-compartment
  zone model including human behaviour;
- ASKFRS [10];

There are a large number of other models that are available to the fire engineers. Models
that can be downloaded from the NIST website [12] currently include the following.

- ALOFT-FTTM – A Large Outdoor Fire plume Trajectory model – Flat Terrain;
- ASCOS – Analysis of Smoke Control Systems;
- ASET-B – Available Safe Egress Time – BASIC;
- ASMET – Atria Smoke Management Engineering Tools;
- BREAK1 – Berkeley Algorithm for Breaking Window Glass in a Compartment Fire;
- CCFM – Consolidated Compartment Fire Model version VENTS;
- CFAST – Consolidated Fire and Smoke Transport Model;
- DETACT-QS – Detector Actuation – Quasi Steady;
- DETACT-T2 – Detector Actuation – Time squared;
- ELVAC – Elevator Evacuation;
- FASTLite – A collection of procedures which provide engineering calculations of various fire phenomena;
- FIRDEMN – Handheld Hosestream Suppression Model;
- FIRST – FIRe Simulation Technique;
- FPETool – Fire Protection Engineering Tools (equations and fire simulation scenarios);
- Jet – a model for the prediction of detector activation and gas temperature in the presence of a smoke layer;
- LAVENT – response of sprinkler links in compartment fires with curtains and ceiling vents;
- NIST Fire Dynamics Simulator and Smokeview – The NIST Fire Dynamics Simulator predicts smoke and/or air flow movement caused by fire, wind, ventilation systems, etc. Smokeview visualizes the predictions generated by NIST FDS.

When freely available models are used, the user must demonstrate that they are competent in its use. These types of model cannot be used as ‘black box’ packages.

**Selection of the appropriate model**

Several factors influence the choice of models to be used. These include range of features, level of detail and degree of validation. In practice other factors such as availability, reliability, cost and user familiarity are also considered. The approach often used is to begin with simple models to gain an overview of the problem and then refine the data input and use a more complex and detailed model to obtain more accurate (or complete) results [13].

Using a combination of modelling techniques, starting with the simpler methods and progressing to more complex ones, can efficiently guide the investigator to a realistic scenario for the incident. However, for this the following are required.

- Awareness of each model’s functionality and limitations so that the results from different models can be understood, for example, layer depths and temperatures from zone models compared with temperature distributions from CFD models.
- The construction of a realistic heat release rate curve drawing on a number of sources including:
  - sparse experimental data and small-scale tests;
  - witness evidence (this may be distorted due to poor recollection of events, stress or intent);
  - engineering judgement (e.g. selection of a fire growth curve).
- Material properties (density, specific heat capacity, thermal conductivity, etc.) of building materials under fire conditions.
- Determination of the pre-fire conditions, such as:
  - materials present;
  - position of doors and windows (open or closed);
  - likely locations of ignition source(s);
  - function of heating, ventilation and air conditioning and building management systems;
  - ambient conditions, including wind pressures.
This may require following a number of possible sequences of events using the results from the models to justify or eliminate different combinations. Of particular concern to the fire investigator are the limitations in the use of these models which are given next.

**Heat release rate**

As mentioned before, there are currently no models available that can calculate the heat release rate of an arbitrary fuel. The heat release rate, either steady state, or time varying, must be input by the user. Since this parameter is often the one that is of greatest interest to the fire investigator, it will be appreciated that this imposes significant limitations on the use of these models. In practice, heat release rates are assumed by the user and estimated from experimental data. There is now a large body of heat release rates for a wide variety of items. Some of the information required may be obtained from the fire investigation. However, unless this is done specifically with the intention of modelling the fire, the accuracy and detail may be of limited value. For example, the UK fire reporting form includes entries for the fire area when first discovered and fire area when first firefighter arrived. In some situations, it may be possible to give an accurate entry (e.g. one pallet of boxes burning when discovered, three when first firefighter arrived). In other cases, an initial observation of the fire may be more tenuous, such as an initial fire area of 1 m². The modeller needs to make a judgement on the accuracy of each data item.

Items in a compartment in a real incident may not correspond to its expected use. While it may be reasonable to adopt the NFPA ‘i²’ heat release rate curves [13] for a particular occupancy for a design calculation this may not always be appropriate for investigation of a real incident.

At the present time, there are very few models that can be worked in reverse, so that the end-state, as found at the incident can be input to the model and then the model is able to compute the starting conditions (such as heat-release rate).

**Other starting conditions**

As mentioned previously, there will almost always be a need to make assumptions regarding the starting conditions for any simulation, such as ambient temperature, wind direction and velocity, state of doors and other ventilation. While many of these variables can be assessed by carrying out a number of runs with different conditions, it is important that they be carefully defined.

**Validity**

The validation history of the model needs to be considered in relation to the actual scenario being modelled, and the investigator needs to be satisfied that the model is sufficiently well proven for the application. Many models suffer from a lack of validation for the application in the field of scientific fire investigation. There is a need for further study and a number of laboratories are pursuing this issue [14,15].

Other areas of concern include:

- sensitivity to inputs;
- risk of misuse;
• sensitivity to data assumptions;
• context of applicability;
• the skill of the user.

**Interpretation of results**

It may be relatively easy to obtain a result from these models, but difficult to interpret or to determine its accuracy. Often expert interpretation is needed and the complexities of the modelling may be difficult to present in a way that can be properly understood by non-specialists in the Courtroom. Detailed numerical outputs can be hard to comprehend, but over-simplified presentation can be misleading.

It also needs to be appreciated that some of the more complex models have significant resource requirements (time and money consuming), in part because of the size of computer needed, and in part because of the data input effort. Thus the needed number of ‘runs’, appropriate to give a valid picture of the event, may be scrimped.

The use of computer models in fire investigation has real potential once many of the practical limitations are overcome and there is now an increasing interest in the use of computer models to assist fire investigation [14–17]. The use of CFD modelling to support the King’s Cross inquiry [5,6] highlighted the potential benefits for both the fire investigation and the wider fire science community. Many of the issues discussed earlier with regards to design, assumptions and reporting apply equally to the use of computer models in Court. Models can often give an erroneous impression of accuracy which can mislead an inexpert jury, especially where there are colourful dynamics displayed.

**Learning lessons from fires**

Fire safety systems differ from nearly every other engineering system in a building since any faults or failures in design, implementation or maintenance will only become apparent during the very emergency for which they are required. With the move into the new era of complex fire safety engineering it is becoming increasingly important that information from real fires is fed back into the fire science knowledge base.

For any building project, the fire engineer must demonstrate compliance with the Building Regulations [18], but these specify only ‘functional’ requirements. Buildings designed to satisfy the recommendations of Approved Document B (AD B) [19] are usually assumed to satisfy the Regulations, and such designs can be assessed and approved by Building Control Officers by reference to AD B. However, buildings designed to the recommendations of well-established and/or widely agreed fire safety engineering codes, such as BS 7974, Code of Practice on the Application of Fire Safety Engineering Principles to the Design of Buildings [20], may also satisfy the regulations. In due course the planned BS 9999, Code of Practice for fire safety in the design, construction and use of buildings [21], is intended to fulfil an intermediate role between AD B and BS 7974.

Other industries, such as the rail industry, adopt a similar approach, where an ‘engineered’ solution needs to demonstrate equivalent safety to the prescriptive Code [22].

It is important to be able to constantly re-evaluate the knowledge base that underpins fire engineering design. An effectively engineered fire safety system for life and property protection requires a co-ordinated interaction of a number of sub-systems which include the
initiation and development of fire, spread of smoke and toxic gases, fire-spread, detection and alarm, suppression, fire service intervention and evacuation. Different fire protection measures are required at different stages of fire development, and this depends upon whether the fire safety system is designed primarily for life safety or property protection. Further complexity arises due to the fact that the timescales for the response of active fire protection measures such as detectors and sprinklers are different from the response time of occupants during evacuation or the structural response time for structural integrity. Assessments of alternative design strategies may depend upon a risk-assessment, where the probability of a particular cascade of events, and its outcome (as measured by deaths, injuries and/or damage), is compared with that of an alternative. ‘Risk-assessments’ have always been implicit in any fire safety design (or any other safety design). But now such risk-assessment techniques are becoming more quantitative and lead to inevitable concerns (such as ‘acceptable’ losses). The reliability of the data used in these risk-based approaches has become critical.

Similarly, computer modelling tools require the input of data and some of this is at present conjectural, or subject to specified assumptions (such as burning rate). There is a need to be able to use fire simulation tools with confidence, where there is a pedigree of validation and a proper understanding of the assumptions, limitations and interpretation of the results.

Examples of the issues that need input from real incidents are listed here.

- **Fire load** What are typical (or design case) fire loads in buildings? Are the current Code assumptions sound (or still sound)?
- **Escape time** How long do real people take to escape? How long is spent thinking, how long travelling, how long going the ‘wrong’ way?
- **Escape route choice** Do people ever use emergency exits?
- **Detection** Do detectors work? Do they operate alarms as assumed? Is the information used as quickly as is assumed?
- **Ignition sources** Are the assumptions regarding sources of ignition sound? Are there some not considered, are there some that really never happen?
- **Fire-spread** Does fire spread in the way assumed? Is it as fast, or as slow, as assumed?
- **Material and structural properties** Do the test methods give a satisfactory indication of the performance of materials or structures in real fires?
- **Flashover** Are the assumptions regarding the processes that lead to flashover valid?
- **Smouldering** What are the mechanisms by which a smouldering fire will go to flaming? How often do burning cigarettes start flaming fires?
- **Visibility** How do people react to smoke in a real emergency? How are decisions made?
- **Tenability** Experiments on people are notoriously difficult. Can the conditions experienced by victims be quantified and correlated with their injuries?
- **Signage** Do people ever look for emergency signs in an emergency? Do they ever obey them?
- **Weather** How and how often do adverse (or benign) weather conditions affect the outcome of a fire?
- **X – the unknown** Are there factors that influence the outcome of a fire that are completely missing from current design analyses?
- **Myths and legends**  Are there factors that are carefully included in design analyses which have absolutely no influence on the outcome of a fire?
- **Fire risk**  How probable (how frequent) are the various events that make up a fire incident? This is possibly the single biggest issue that requires a substantial input from fire investigations.

A few examples of how information from fire investigations have fed back into fire engineering include:

- Woolworths (Manchester), May 1979: this incident showed that stacked goods could shield a significant part of the fire load from the sprinkler spray.
- Stardust Disco (Dublin), February 1981: this fire demonstrated the differences in fire behaviour of material used vertically from the same material used horizontally.
- King's Cross (London), November 1987: the investigation into this incident led to the identification of the ‘trench effect’.
- Four Seasons Hotel (Aviemore), January 1995: this fire identified the effect of poor cavity fire stopping and the potential effects and impact of adverse weather conditions.
- The Channel Tunnel, November 1996: this event demonstrated the importance of the management of fire safety.
- Ladbroke Grove (London), October 1999: The post-crash flashed-over fire resulted from the ‘wick’ effect when two components, each not easily ignited, were in combination.

Other, less well known, incidents have highlighted the importance of design components such as nail plates in roof construction, plastic eaves, weather-proof cladding, sandwich panels, candles, television sets and video cassettes.

As fire safety engineering develops, the effectiveness, performance and reliability of the passive, active and procedural fire safety systems being introduced into buildings becomes more critical if lives are to be adequately protected from a fire. The data, assumptions, methodologies and models that go into fire safety engineering designs must be well founded and reflect what happens in the ‘real’ world.

**Conclusion**

Because all fire incidents are different, it follows that all reconstructions are different and it is almost impossible to plan ahead. Nevertheless, some knowledge of what is possible and what is valuable, can help planning for a re-creation early in an investigation.

Lines of responsibility must be defined; there is a need for clear management and good communications from start, and, for the laboratory, it is essential to identify the clients, or the client’s agents, to specify the client's needs and hence to define the objectives of the re-creation. Reconstructions are expensive and will nearly always be resource limited, so it is necessary to identify any constraints (mostly time or money) and existing knowledge of the incident. Any assumptions that are needed must be agreed and documented.

The Report of the re-creation must clearly state any assumptions and needs to be written to ensure that it will be understood by a non-technical audience and stand up in Court under hostile questioning.
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Appendix A: The ‘standard’ fire tests

Fire resistance

Fire resistance is a measure of the ability of a construction element to stay up and prevent the passage of fire, heat or smoke for a specified period, usually long enough for occupants to escape. The test methods are given in BS 476-Part 20, etc. and presume that a quite severe (post-flashover) fire has developed.

Reaction to fire

Reaction to fire tests assess a number of properties and materials. Ignitability assesses whether a material is likely to catch fire. Combustibility assesses whether a material will burn and add to a fire when subjected to an existing fire. Spread of flame assesses whether the fire will spread over the surface of the material (especially wall linings).

The following Standard tests are those for building products:

BS 476-7:1997 Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products.
BS 476-10:1983 Fire tests on building materials and structures. Guide to the principles and application of fire testing.
In addition, there are specified fire tests for many other products and industries. The fire investigator will need to determine the appropriate tests for the particular product with which there is concern.

Appendix B: About FRS

FRS is one of the largest fire laboratories in the world and carries out fire investigations for Government and other agencies to learn lessons to improve regulations. However, FRS is only rarely involved directly with forensic investigations and so can provide independent specialist help to other investigators. FRS (which now includes the Loss Prevention Council, LPC) is the fire division of the Building Research Establishment Ltd, at Garston, Watford, UK. FRS has over 100 research and technical staff and has specialised small- and medium-scale test laboratories, Standard fire testing facilities and a 10 MW Burn Hall. Outdoor facilities are used for very large or smoky tests. FRS offers consultancy advice on all aspects of fire science that calls upon the expertise and experience of our scientific staff, and specialised research and testing facilities and fire investigation is fully integrated into the research programme. Specialists work in all the areas of fire science from materials behaviour to...
human behaviour and management and the work is applied to buildings, structures (offshore) and transport, including aerospace, marine, rail, road and transport infrastructure, tunnels.

The UK Office of the Deputy Prime Minister (ODPM) previously the Department of Transport, Local Government and the Regions (DTLR); previously Department of Environment, Transport and the Regions (DETR); previously Department of Environment (DoE) has long recognised the need for information from real fires in order to directly inform ministers of high profile incidents, to ensure that the guidance ODPM publishes reflects what happens during fires in real buildings, and to ensure that the whole ODPM fire research programme is supported and underpinned by information from actual relevant incidents. ODPM has funded work on both investigations into major incidents and the routine investigation of real fires by experienced staff at the FRS/BRE since the early 1970s. Consequently, the unique FRS expertise in this non-forensic type of fire investigation, developed for and supported by ODPM, has been called upon for many major inquires, including Piper Alpha (1988), the Channel Tunnel fire (1996), the Ladbrook Grove rail incident (1999) and the Yarl’s Wood Detention Centre fire (2002). With the move to the functional rather than prescriptive regulations in 1985, information from real events became of even greater value to ODPM. Since 1989 this need has primarily been met by the work of the Fire Investigation Team at FRS. This team has the remit of examining fires with implications for current regulations, codes and standards, fires which have implications for current research (which itself is aimed at the development of guidance) and fires where there is a special interest by ministers or other officials. The team has access to all the research staff at FRS and, more widely, across the Building Research Establishment (BRE) and these staff can provide specialist input to an investigation about almost any aspect of the fire, including, for example, the performance of building types, ventilation systems, materials and fire-spread. The information gathered can be presented to meet particular ODPM requirements but with the primary function of giving an early warning of topics that need to be addressed during updating of documentation. This continuous review also is able to underpin the usefulness and effectiveness of current guidance by highlighting its successes.

It is this breadth of approach to understanding the implications from fires in buildings that has been of proven use. For example, investigations of factory fires contributed to identifying the problems associated with large single-storey buildings and the involvement of sandwich panel constructions, and was the basis for changes in the edition of the AD B issued in 2000. Investigations into fires involving truss-rafter roofs led to an ODPM research programme on this topic. In many other cases the effectiveness of current guidance has been demonstrated. BRE has also been able to provide similar information to the Scottish Office, the Northern Ireland Office, Home Office, DTI where appropriate. As well as site visits by experienced FRS staff, information is gathered from a variety of sources including the police, fire brigades, forensic scientists and fire consultants in the private sector. Investigators from these other agencies are met by FRS staff both on and off site. However, all of these other bodies are almost exclusively concerned with establishing the cause, identifying the blame for the occurrence of a fire or determining liability. The involvement of FRS investigators on behalf of ODPM does not compete with any of these investigators and they have always responded positively to requests for information in the national interest of life safety. However, information is occasionally delayed if there is a court case impending and matters are sub judice. In order to maintain these important working relationships, FRS in general avoids commissions for private forensic investigations,
but is involved in a number of UK and European fire investigation fora. Information is also obtained from literature reviews and examination of the ODPM fire statistics database.

Few, if any, other countries have adopted this continuous and systematic approach to examining the implications from generic examples of fire (see Appendix C also).

Other support for fire investigation includes demonstrations for training seminars and workshops for information transfer, the analysis of statistics (using the UK fire reporting database), computer modelling (using zone models, computational fluid dynamics, and virtual reality) and chemical and elemental analysis (including electron microscopy, ion chromatography, GC and GS–MS).

Appendix C: Fire test laboratories

The following organisations offer laboratory services that can be of assistance to fire investigators. (Note: forensic laboratories and overseas laboratories are not included.)

FRS (Incorporating the Loss Prevention Council (LPC))
Building Research Establishment
Garston, Watford, WD25 9XX, UK
Phone: +44 (0) 1923 664960
Fax: +44 (0) 1923 664910
E-mail: shippm@bre.co.uk

Health and Safety Laboratory
Process Hazards Group
Harpur Hill, Buxton
Derbyshire SK17 9JN, UK
Phone: +44 (0) 1142 892007
Fax: +44 (0) 1142 892010

Fire Safety Engineering Research and Technology Centre (FireSERT)
University of Ulster
Jordanstown, Newtownabbey
BT37 0QB, Northern Ireland
Phone: +44 (0) 1232 368701
Fax: +44 (0) 1232 368700

Fire Safety Engineering Group
School of Computing and Mathematical Sciences
University of Greenwich
30 Park Row
London SE10 9LS, UK
Phone: +44 (0) 208-331-8730
Fax: +44 (0) 208-331-8925

Health and Safety Laboratory
Stanger Science and Environment
Acrewood Way
St Albans,
Herts
AL4 0JY, UK
Phone: +44 (0) 1727 840580
Fax: +44 (0) 1727 816700

Fire Safety Engineering Group
Crew Building
University of Edinburgh
Edinburgh EH9 3JN
Scotland, UK
Phone: +44 (0) 131-650-7161
Fax: +44 (0) 131-667-9238

TTL Chiltern (TRADA)
Chiltern House
Stocking Lane
Hughenden Valley, High Wycombe
Buckinghamshire HP14 ND, UK
Phone: +44 (0) 1494 563091
Fax: +44 (0) 1494 565487

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