A Review of Sociological Issues in Fire Safety Regulation

Citation for published version:
Spinardi, G, Bisby, L & Torero, JL 2016, 'A Review of Sociological Issues in Fire Safety Regulation' Fire Technology, pp. 1-27. DOI: 10.1007/s10694-016-0615-1

Digital Object Identifier (DOI):
10.1007/s10694-016-0615-1

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Fire Technology

A Review of Sociological Issues in Fire Safety Regulation

ABSTRACT

This communication presents an overview of contemporary sociological issues in fire safety. The most obviously social aspects of fire safety – those that relate to the socioeconomic distribution of fire casualties and damage – are discussed first. The means that society uses to mitigate fire risks through regulation are treated next; focusing on the shift towards fire engineered solutions and the particular challenges this poses for the social distribution and communication of fire safety knowledge and expertise. Finally, the social construction of fire safety knowledge is discussed, raising questions about whether the confidence in the application of this knowledge by the full range of participants in the fire safety design and approvals process is always justified, given the specific assumptions involved in both the production of the knowledge and its extension to applications significantly removed from the original knowledge production; and the requisite competence that is therefore needed to apply this knowledge. The overarching objective is to argue that the fire safety professions ought to be more reflexive and informed about the nature of the knowledge and expertise that they develop and apply, and to suggest that fire safety scientists and engineers ought to actively collaborate with social scientists in research designed to study the way people interact with fire safety technology.

Keywords: Sociology, fire safety, knowledge, expertise, regulation.

1.0 INTRODUCTION

Fire safety knowledge and engineering expertise has advanced a great deal over the last few decades. Specialist journals report the latest findings; sophisticated simulation models provide tools for modelling fire, smoke, evacuation, and structural outcomes; and ambitious new buildings incorporate innovative designs that push forward the boundaries of fire safety engineering and question the limits and applicability of conventional prescriptive design guidance. In many parts of the world, fire deaths have also seen a steady decline over these recent decades [1].

However, a sociological perspective requires us to look beneath the surface, and ask hard questions about the depth, nature, and rigor of fire safety knowledge, and the mechanisms through which existing knowledge is applied in practice. Here our focus is on perspectives from the sociology of scientific knowledge and the sociology of technology that elucidate the social factors that are central to both knowledge production, and its dissemination and application [e.g. 2-7]. These perspectives are particularly apposite to fire safety because they emphasise the contingent nature of knowledge claims (e.g. in judging whether test results are sufficiently representative) and the effects of social organisation on technological practice (e.g. how regulatory practices affect fire safety implementation). Adopting a sociological perspective, in which we seek to understand the role of social factors in fire safety, helps us to address some key issues. Do fire safety solutions take sufficient account of social context? Can we develop better ways to learn and apply the lessons of fire disasters? Do the fire safety professions truly understand (and thus deliver on) society's expectations with respect to fire safety? Do all stakeholders have sufficient understanding of the fundamentals of fire safety to underpin the regulatory shift towards performance based design? Indeed, can fire 'safety' be rigorously quantified? And if not, are current practices increasing risk or leading to excessive and expensive fire safety measures? In general, what can be done to enhance the development and uptake of fire safety science and to further promote best practice across fire safety engineering?

A classic response to these questions would be to call for greater levels of research funding to increase the scientific and technical knowledge base available for fire safety designers, regulators, and practitioners. But clearly if existing knowledge is not being properly exploited by all requisite stakeholders, or if fire safety research fails to lead to real progress, then further engineering research alone cannot lead to optimised outcomes in practice. Instead it is worth considering the possibility that making additional progress in fire safety may depend, at least in part, on a deeper understanding of both the social nature and social context of the problem.

Our aim is to argue for all fire safety specialists to reflect more on the nature of the knowledge and expertise that they develop and apply. What follows is a working through of sociological perspectives on fire safety that is not intended to criticize or judge current stakeholders (fire safety engineers in particular), but rather to stimulate reflection. We seek to open up debates, rather than close them off; to pose questions, rather than answer them. It is also noteworthy that many of the ideas and questions raised have relevance for other forms of engineering, for instance structural engineering, however to different degrees and in subtly different ways.

Given that both fire risks and fire protection measures are all around us in the built environment, the essentially social nature of fire safety is obvious at one level. Fires are not only often the result of human activities, but also the way that fires develop, and the extent to which people react and are able to escape, all hinge on human behaviour and on social (and economic) organization. In addition, *implementation* of fire safety measures and *understanding* of the underlying processes have strong social components. What follows makes the case for a sociology of fire safety, arguing that all aspects of fire safety are inherently social in nature, or are fundamentally influenced by social factors, and that an understanding of the ways in which this shapes the provision of fire safety will help scientists and engineers to more effectively use (and improve) their technical knowledge. Although many of the points we make are not novel individually, we believe this to be an original comprehensive synthesis of the role of social factors in fire safety that we have identified within the literature and the fire safety engineering professions. The common thread that runs through this paper is our focus on the processes by which the disparate sources of fire safety knowledge (from statistics, fire investigations, experiments and tests, and first principles calculations) are assembled and made use of in fire safety engineering.

We begin with some obviously social aspects of fire safety that relate to the *socioeconomic distribution of fire casualties and damage* (it is perhaps telling that historically most of the buildings in question are those that had the least explicit involvement of fire safety professionals in their construction and maintenance). Next we describe how society has sought to mitigate fire risks through regulation, and how the current shift towards fire engineered solutions poses particular challenges for *the social distribution and communication of fire safety knowledge and expertise*. In particular, the partial displacement of prescriptive regulatory approaches appears to shift responsibility towards forms of self-regulation that depend on the professionalism and technical competence of fire safety engineers, but it is not yet clear that the profession as a whole has fully embraced appropriate mechanisms for accreditation to ensure sufficiently high standards across the industry [8], or indeed whether self-regulation is well-suited to a form of risk that is infrequent, uncertain, and probabilistic in nature. Finally, we discuss *the social construction of fire safety knowledge*, raising questions about whether the level of confidence in the application and approval of this knowledge is optimal given the specific assumptions involved in both the production of the knowledge and its extension to applications that may be somewhat removed from the original knowledge production.

2.0 PART I: FIRE IN SOCIETY

2.1 Socio-economic factors and fire outcomes

The pervasive social nature of fire risks and solutions is easily observed. Our built environment offers many benefits but also brings with it risks, including those from fire. These risks can be ameliorated through technical means (e.g. the design of buildings and the materials used), but in many cases human behaviour remains central to both fire initiation and to outcomes. In particular, socioeconomic circumstances play a major role, with most fire deaths occurring in domestic settings, and rates of fires and casualties correlated with socioeconomic status [9]. Generally speaking, fire deaths are decreasing in Europe, North America, and some other jurisdictions (though fire statistics remain limited or lacking in many parts of the world). For example, in 2013-14 the United Kingdom saw 322 fire-related deaths, the lowest figure for the last 50 years (for comparison there were 1775 deaths due to road accidents in 2014), in keeping with a general downward trend over recent years (the highpoint was 967 deaths in 1985-86) [10]; for road deaths as a comparator, see [11]. Non-fatal fire casualties have seen a similar reduction in recent decades.

Of the 322 UK deaths in 2013-14, 80% were due to fires in dwellings, with only 17 in other buildings (fewer than in road vehicles or outdoors)[10]. In addition, the proportion of dwelling fires that led to death was much greater than for other buildings, including other types of residential buildings (e.g. care homes, hotels and hostels) with 6.6 deaths per 1000 dwelling fires compared to 1.0 per 1000 for other building types [10].

There was also significant variation in fire deaths between countries in the UK, with Scotland having the highest rate at around 6 deaths per million of population compared to 5.5 in Wales and 5.1 in England [10]. It is noteworthy that Scottish fire statistics highlight alcohol and/or drugs as a significant factor. Over the three years 2009-10 to 2011-12, 44 out of a total of 138 fire deaths in Scotland were associated with suspected alcohol or drug use [12].

The recent history of domestic fire safety in the UK and elsewhere shows that simple and inexpensive solutions can be very effective, if they are installed, operated, and maintained correctly. One of the most significant changes in the UK in recent years has been the installation of smoke alarms in dwellings. The proportion of households with smoke alarms increased from 8% in 1988 to 88% in 2011 [10]. Working smoke alarms are clearly associated with lower rates of death. For example, in 2013-14 the death rate in fires was 4 per 1000 for fires that were detected by an alarm compared to 8 per 1000 for undetected fires [10]. US data show a similar pattern, with death rates for reported fires about half for fires in homes that had a working smoke alarm compared to those in homes that did not [13]. Socioeconomic factors may also influence uptake of such technologies, and additional research in this area may be warranted.

‘Chip’ pans may also be increasingly uncommon, with British fires arising from this cause declining by more than 75% in the ten years up to 2011-12 (an unintended consequence of the emergence of chips that can be oven-cooked), however cooking appliances remain the largest cause of dwelling fires [10]. Nonetheless, cooking related fires only accounted for 30 UK fatalities out of the 322 total, which might ‘reflect the relatively minor nature of many cooking-related fires and the fact that many cooking fires occur when the victims are alert at the time of the fire’ [10]. In cases of fire deaths in dwellings, cigarettes have been identified as the most important cause of ignition, accounting for over a third of UK fatalities in 2013-14 [10].

US data again show similar patterns, with 84% of civilian (i.e. non-fire service) deaths in 2014 attributed to dwelling fires [14]. From a peak of 6015 in 1978, US domestic fire deaths had dropped to 2745 in 2014, though the decline over the years has been neither smooth nor continuous [14].

Alongside these broad historical trends are comparative data that strongly suggest socioeconomic explanations for fire outcomes. Studies of US cities according to census areas show that those areas with the lowest average incomes have the highest rates of fire [15]. A wide range of factors showed some significant correlation with fire rates – including home ownership, education levels, numbers of one parent families, and race – but these were all also strongly related to income. If analysed from the viewpoint of neighbourhoods then areas suffering from economic decline, with higher levels of abandoned buildings, are particularly at risk, as accidental fires are likely to have more severe consequences and arson is more likely to occur [15].

Major US cities have long suffered from high levels of arson. For example, in 1994 arson was the biggest cause of fire deaths in US metropolitan areas [15]. Changes in the urban landscape in the US – both what has been called the ‘white flight’ to the suburbs that began in the 1950s and the more recent decline in old manufacturing industries – have left many urban areas with very low average incomes. As a recent example, Detroit suffered an estimated 5000 arson fires in 2012, though the figure is necessarily approximate because the Detroit Fire Department only had sufficient resources to investigate about one in five suspicious fires [16]. Likewise in the UK, overall levels of arson mask much higher regional variations. Nationally, according to data collected by the British fire services on fires they were called to, about 12% of dwelling fires were started deliberately [10]. However, in 2013 the Cleveland Fire Brigade [17] reported that seven out of ten fires in their jurisdiction were the result of arson, a figure matched by those for Wales in 2010/11. A 2003 survey of arson in England and Wales claimed that since the early 1990s 1200 deaths and 32000 injuries had been caused by arson, with an average week resulting in one death and 55 injuries [18].

The causes of arson are clearly social. In a city like Detroit many cases are likely to result from attempts to claim insurance for properties that are no longer saleable, as well as from disaffection with the state of neighbourhoods. In other cases, for example arson attacks on schools, the more specific social issues concerning the alienation of young people are likely to be involved, and in the UK most arson interventions are aimed at modifying the behaviour of young people [18].

Statistics such as those presented here constitute an important source of knowledge about fire safety, with the proviso that their value is heavily dependent on the way that the original data are collected. Moreover, such statistics simply show correlations that are indicative of problems and solutions rather than demonstrating cause and effect. Nevertheless, it is widely believed that the fire problem is greater in the poorer economies of the world, and particularly in informal settlements, and better data collection and statistical analysis would be an important step towards addressing this problem.

2.2 Taking account of 'the social' in technical solutions

These statistics pose challenges for scientists and engineers. The strong correlation of socioeconomic factors with fire incidents and casualties may lead one to suggest that these types of fire safety issues should be considered 'social' rather than 'technical', and therefore outside the remit of scientific and engineering approaches to fire safety. However, this could be seen as a dereliction of social responsibility and would also require a revisionist account of the history of fire safety. 'Socio-technical' expertise has played a major part in historical fire safety advances, and this tradition ought to continue whilst adapting to changing circumstances in the built environment. Technical solutions cannot necessarily make people behave better (though a harmonious built environment may help), but they may ameliorate the outcomes of people behaving badly.

In practice, tackling the social stratification of fire risks may be more a matter of political will, economic priorities, and good governance, than devising new technical solutions; notwithstanding the cases where technical solutions are informed by, and sensitive to, social considerations. Societal perceptions of risk are complex in nature, with many factors influencing how people view risks and the extent to which they act to mitigate them (individually, organizationally, and politically) [19, 20]. Risks can of course be quantified and calculated, as with the risk assessments carried out by industries such as nuclear power [21], or indirectly through cost-benefit analyses performed to inform decisions about fire safety measures such as domestic sprinklers [22]. However, when it comes to complex and rare events, these kinds of risk calculations typically involve a sufficient number of questionable assumptions about the relevant inputs for their results to be ignorable where convenient, on account of political, organizational, or individual beliefs and interests.

More, and more detailed and reliable, fire statistics would help bolster evidence-based decision-making. At present many countries have inadequate or no formalized systems for collecting such data. Although existing solutions – such as smoke alarms and compartmentalization – can reduce casualties in certain situations, the evidence on which to base policy decisions is often limited (and therefore contested). Much depends on the interaction of human behaviour with technology (e.g.

making sure smoke alarms are working; for a study of why smoke alarms are not maintained, or even turned off, see [23]), and evidence-based decision making about such technologies requires comprehensive study of fire safety features *in situ*. It is thus worth asking whether fire safety scientists and engineers could obtain more realistic data through collaboration with social scientists in research designed to study the way people interact with fire safety technology. In this way the fire safety community could provide better data on the effectiveness (and cost-effectiveness) of different technical approaches, while recognising that regulatory frameworks and policy initiatives are unlikely to be driven purely by evidence (and acknowledging that such evidence can never be purely 'technical', especially if cost assumptions are involved). Some technical solutions – for instance sprinklers in domestic properties – may have public and political appeal as well as strong commercial backing, even though the evidence over their cost-effectiveness remains contested. Studies of sprinkler effectiveness are generally econometric in nature and assume that sprinklers will reduce fire size and thus reduce casualties. Such studies are dependent on the cost assumptions used, including those that vary according to local calculations of how life is valued. For example, a BRE report on 'Cost Benefit Analysis of Residential Sprinklers for Wales' prepared for the Welsh Government concluded that, 'fitting sprinklers in all new residential premises in Wales is not cost effective' [22]. In contrast, an earlier New Zealand study found residential sprinklers to be generally cost-effective [24].

3.0 PART II: REGULATION

3.1 Regulation by prescriptive rules

Traditionally a key factor in reducing fire safety risk has been society's capacity to regulate building activities to reduce fire related risks in the resulting structures (and communities). Regulations have often emerged as piecemeal responses to particular fire disasters, building up over the years into a comprehensive set of necessarily approximate buildings codes that prescribe rules and guidelines according to the type, location, occupancy, and use of buildings.

To quote the classic example, the 1666 Great Fire of London led to King Charles II's famous declaration that 'no man whatsoever shal presume to erect any House or Building, great or smal, but of Brick or Stone, and if any man shal do the contrary, the next Magistrate shal forthwith cause it to be pulled down', and that 'all other eminent and notorious Streets, shal be of such a breadth, as may with Gods blessing prevent the mischief that one side may suffer if the other be on fire' [25]. The Rebuilding of London Act 1666 set out more detailed building regulations, affirming the requirement that brick or stone should be the main building materials, and setting out specific requirements for the width of walls (including party walls) according to the type of building. Such historical regulations have (and in some cases still do) profoundly influenced the very fabric of urban environments in the developed world.

Many regulations that persist in some form or other to the present day stem from such long past events, sometimes in circumstances that may no longer pertain. In some cases, such as the requirement for a fire evacuation time of no more than 2½ minutes, anecdotally stemming from the time taken to play the UK national anthem during a 1911 fire at Edinburgh's Empire Palace Theatre, the origins of regulations may appear to be particularly idiosyncratic [26]. Nevertheless, many of the rules that resulted have since proven themselves to be useful and defensible in hindsight.

Sometimes these rules have taken the form of sweeping, common-sense solutions lacking a detailed scientific understanding of the particular fire safety problem, but sometimes – as with examples such as the Piper Alpha or King's Cross fires – the regulatory changes have been based on in-depth analysis [27, 28]. These building codes appear to have served society well in reducing fire damage, deaths, and injuries [1], with a focus on four main issues to ensure life safety: (1) evacuation, (2) fire and smoke containment, (3) fire-fighting access and facilities, and (4) structural collapse prevention. For example, the five requirements in British building regulations cover these four main areas [29]. However, to the knowledge of the authors, an element that is lacking in the literature is an in-depth analysis of the costs and economic implications of these regulatory requirements.

3.2 Social interests and regulation

It is important to note that society's responses to fire disasters are mediated by politics, and often complicated by the considerable challenge of retrospective analysis based on limited data. For example, following the 1906 San Francisco earthquake/fire, concern about the effect that being labelled an earthquake zone would have on investment led local business, media, and government to launch a concerted campaign to emphasise the fire, which was considered to be preventable, and downplay the earthquake, which was not. Thus the San Francisco Real Estate Board explicitly agreed that no mention should be made of 'the great earthquake;' instead it would be known as 'the great fire' [30]. Geologists interested in investigating what had happened 'were advised and even urged over and over again to gather no such information, and above all not to publish it' [31].

In addition, attempts to understand whether 'the inadequacy of fireproof covering' was a factor in building collapse after the earthquake, an already challenging task given the general level of destruction, were confounded by the damage caused by the dynamiting used in an attempt to create firebreaks. Sent to investigate, Captain John Stephen Sewell of the United States Engineers Office complained that it 'was not possible, in the majority of cases, for me to get the debris out of the way, and satisfy myself by a personal observation, as to whether the damage was done by fire or by dynamite' [30]. The oft-cited statistics that reported 10% earthquake damage and 90% fire damage came from a compromise about how much insurance companies were prepared to pay (as earthquake damage *and* resulting fires were typically not covered), and not from any actual measurement of damage [30]. Moreover, the framing of the disaster as being primarily a fire disaster led to the main response being the responsibility of the city Fire Department, and thus directed at improving fire fighting capabilities rather than the ability of buildings to withstand fire (or indeed earthquake). While water supplies were greatly improved, the rush to rebuild meant building regulations were neither consistently strengthened nor rigorously applied in the years that followed [32].

As this example shows, perhaps to an unusual extent, the impetus for regulation driven by major fires does not occur in a social vacuum. Fire disasters not only led to building regulations; they also led to the development of fire prevention technologies, and to the establishment of fire and rescue services and the infrastructure to fight fires. Given their important role, the fire and rescue services became established as a de-facto source of expertise, as well as an important lobbying power. The fire safety industry too gradually became a significant social group, with interests in influencing fire safety regulation.

Industry's role has often been beneficial. For example, the desire by US insurance companies to standardize the implementation of sprinkler systems led to the formation of the National Fire Protection Association (NFPA) in the 1890s, with subsequent reductions in fire losses, particularly in industrial buildings. In a similar manner, the specialist insurance provider FM Global has for many years operated one of the world's major fire research laboratories, producing knowledge of use beyond FM Global's primary insurance remit.

However, commercial interests cannot be presumed to be entirely benign in their influence, nor, moreover, should they be seen as a unified lobby group. In particular, it is possible to characterize industry groupings according to types of product, such as 'steel' versus 'concrete,' and 'active' versus 'passive' approaches to fire safety. These competing commercial interests are potentially important in the way that they seek to influence the 'code committees' that formulate new regulatory guidelines and standards.

3.3 The limits of prescription

Prescriptive codes have generally served societies well. For any particular class of building, prescriptive codes impose specific requirements for fire safety measures that are deemed to satisfy societal requirements for safety. However, the standardization of prescriptive design solutions and the prevalence of common sense derivations and observation-based solutions are necessarily accompanied by coarse approximations and a comparatively large margin of safety, sometimes with limited use of scientific understanding. Thus, the unthinking use of prescriptive codes has attracted criticism because such an approach may make buildings more expensive than they might otherwise be, is less responsive to changing circumstances, and can be inflexible as regards individual design situations. Prescriptive design solutions, using necessarily simplified design tools, may either waste resources or fail to provide the expected level of safety if used where they are not strictly applicable. Thus, one source of pressure for a move away from prescriptive codes has come from political and commercial influences that seek to apply increasing fire safety knowledge in the interests of *deregulation*.

It is also worth noting that the very success of prescriptive codes in reducing fire deaths paradoxically undermines a key aspect of an approach based on learning from disasters. With major fire incidents becoming less common, there is less feedback to update the regulations. If, as Drysdale [33] has put it, 'Progress relied on lessons learned from failure', then fewer major fires might mean fewer lessons learned. Although knowledge has advanced greatly since the Great Fire of London, and crude pragmatic responses may no longer be appropriate, there is still an imperative to learn from fires because they provide the most authentic feedback regarding potential failings in fire safety measures or design. They also serve to identify any new design weaknesses introduced because of other innovations in the built environment.

Given the (thankfully) limited numbers of major fires in many jurisdictions, our ability to learn these lessons is limited. Rather than fire investigation remaining a local matter, it would be useful to have an international, industry-wide approach to coordinate learning from all major fires wherever they occur, perhaps in a manner analogous to the way that major airliner crashes are investigated by local jurisdictions, but under the international standards and practices set out in the International Civil Aviation Organization Annex 13 [34]. In a parallel field, the Institution of Structural Engineers oversees an Earthquake Engineering Field Investigation Team (EEFIT), which is a group of structural engineers who visit major earthquake sites globally and report on building seismic performance. Thus, when it comes to earthquakes and structural engineering there exists an explicit feedback loop. However, while some fire engineering case studies are reported publically and in the literature, there is no "FEFIT" group for Fire Engineering and thus no similarly coordinated feedback for the benefit of the Fire Safety Engineering community.

The absence of detailed and recurring empirical feedback on fire safety outcomes leaves a knowledge gap that has been filled in part by Fire Safety Science. Advances in fundamental understanding of fire phenomena, in human behaviour, and in structural responses to fire, have enabled a gradual shift in the nature of fire safety regulation. The claim is that if fire safety solutions can be designed and assessed according to the latest knowledge, rather than required to meet historic prescriptive rules, then buildings can be more innovative, more functional, more sustainable, and safer – given that their safety level may be established rather than deemed, and possibly even enhanced through this assessment. Moreover, tolerances can be judged more finely, and unnecessary margins of safety reduced.

This shift towards functional objectives is embodied not only in more science-driven prescriptive rules, but also in the increasing use of 'fire engineered solutions,' or what is widely (if imprecisely) described as Performance Based Designs (PBD). While fire safety design has always been undertaken with the objective of providing an adequate level of building performance in fire, modern performance based design seeks to use the best available knowledge to find the best fire safety strategy that results in the most efficient building, without sacrificing the societally tolerable level of fire hazard. As defined by the International Organization for Standardization (ISO/TC92/SC4), fire safety engineering is: 'The application of engineering principles, rules and expert judgment based on a scientific appreciation of the fire phenomena, of the effects of fire, and of the reaction and behaviour of people, in order to: (a) save life, protect property and preserve the environment and heritage; (b) quantify the hazards and risks of fire and its effects; (c) evaluate analytically the optimum protective and preventative measures necessary to limit, within prescribed levels, the consequences of fire' (quoted in [35]).

However, increased use of PBD solutions rather than adherence to simple rules may also present challenges. In particular, it raises important questions about the extent to which fire safety knowledge is understood and used by all of those involved in the design, construction, and operation/management processes, where responsibility for regulation lies, and about how the fire safety community understands and quantifies the level of acceptable fire hazard.

3.4 The challenges of performance engineering

The crux of the critique of a predominantly prescriptive approach to building design and regulation is that prescriptive rules are often rooted in long-past historical events, and despite regular updating may have not kept up with innovations in design and construction. New building techniques and materials could thus mean that current prescriptive rules no longer achieve the assumed level of fire safety. As Brannigan has noted: 'Buildings codes make buildings legal; they do not make them safe' (for example, in his presentation at the Lloyd's Register Foundation/University of Edinburgh Seminar in Fire Safety Engineering, Gullane, Scotland, April 30, 2013). In addition, prescriptive regulations are seen to impose unnecessary requirements that may inhibit innovation, or add unnecessary costs.

By the second half of the twentieth century, prescriptive fire design rules specified, in considerable detail, what was required for particular classes of buildings. For example, by the end of the 1970s the building regulations for England and Wales totalled 307 pages of guidance, and were, as described by Law, 'very prescriptive and understood mainly by lawyers' [36]. The latest US (mostly prescriptive) fire codes found in the International Building Code (IBC) now total over 700 pages. In some cases (e.g. the British rule that a horizontal escape route should not be within 4.5m of an opening such as an escalator or atrium [37]) the precise origins and logic of the prescriptive rules (sometimes referred to as ‘magic numbers’) are unknown even to many skilled fire safety engineering practitioners [38].

In principle, British regulations have become less prescriptive since the Building Act 1984, which came into force in late 1985. However, although the guidance provided in the resulting regulations (e.g. as found in Approved Document B in England and Wales [37]) only recommends ways in which the fire safety requirements can be met, practitioners (both building control and fire brigades as regulators, and architects/engineers and their clients proposing schemes) have often followed the prescriptive rules in practice. Indeed, many fire safety practitioners still operate largely within a prescriptive framework because of a view (real or perceived) that following the stated rules provides reassurance to the regulators that fire safety standards are being upheld – i.e. that a tacitly agreed and historically demonstrated ‘level of safety’ has been achieved. For the engineers and their clients this may provide some reassurance that approval will be granted more quickly. This reduces the ‘approvals risk’ feared by developers, which appears to be a deterrent to stepping outside the directives of prescriptive design rules.

Several jurisdictions (UK, USA, Australia, New Zealand, etc.) allow designers the option to deviate from prescriptive design rules through the use of PBD fire engineering approaches, though some (e.g. the USA) remain more prescriptive in practice than others. In some cases prescriptive rules may be followed except for those parts of a design where the guidelines are overly restrictive in inhibiting the architect’s vision, where the building site has physical limitations that cannot be accommodated by the prescriptive rules, or where a more performance based approach offers solutions that are clearly better (i.e. safer or more rational) or offer significant savings.

Many authors have previously commented on the benefits and potential pitfalls of more performance based approaches to fire safety engineering design [e.g. 19, 20, 39-42], and have raised questions regarding the practical application of PBD in fire safety engineering, including issues such as: technical knowledge gaps and education needs [36, 39], differing perceptions of, and expectations around, mitigation of fire risks by different stakeholders [19, 20], quantification and demonstration of acceptable levels of ‘performance’ [20, 40], accountability in differing regulatory regimes [41], and politicization of decision making [42]. A particularly useful review of the relevant issues, some of which are discussed below, is given by Alvarez et al. [42].

In the case of prescriptive regulatory approaches, approval ultimately depends on adjudication by the authority having jurisdiction (AHJ) as regards its interpretation of the applicability and intentions of the rules. Not only can judgment be necessary to decide whether a specific rule is applicable to a particular project, but also the rules may require interpretation because, if too narrowly framed, they could be difficult to apply generally. However, this has led to criticisms such as that ‘prescriptive guidance is awkward, ambiguous and complicated to use’ [43]. Hence the emergence of a professional group of fire safety code consultants, whose expertise is in interpreting and re-interpreting the ‘intent’ of the rules to help clients navigate prescriptive codes.

Science and Technology Studies (STS) tells us [e.g. 2-7] that social relations matter in such an approvals process because different individuals may take a different view on the intent of the same regulation, and good relationships and trust between players can smooth the process. Former fire service personnel are sometimes employed by engineering firms not just for *what* they know, but also for *whom* they know within the approvals process. And longstanding relationships can lead to regulators having trust in the competence of specific architects, engineers, and builders, thus enabling novel designs and strategies to be approved more easily.

Whereas under a prescriptive approach the AHJ must interpret and adjudicate on the applicability and intention of specific fire code rules, with a PBD approach approvers are required to *understand* and adjudicate on fire safety *knowledge* claims and applications. In essence, a shift towards PBD marks a shift away from regulation based on judgements of the law, to regulation based on judgements of the laws of science. Being expert in application of the rules is necessary but no longer sufficient; being expert in the underlying science is now essential. However, this raises the obvious question of whether the traditional approval authorities for fire safety are (or can become) sufficiently expert in the fundamentals of fire safety science and its engineering application to provide the necessary oversight. In particular, we are faced with sociological questions of how knowledge claims about fire safety knowledge are constructed and assessed, and who is deemed competent to make such judgments.

3.5 Deregulation and/or self-regulation?

One solution would be to replace external regulation as we know it with some degree of self-regulation. This has long been the practice in aviation regulation (admittedly an industry sector that is markedly different from fire safety in a number of regards), where it was recognised decades ago that the complexity of aircraft technology meant that regulators such as the US Federal Aviation Administration (FAA) could not stay abreast of the work of the manufacturers without incurring excessive costs. Instead, the FAA delegates much of its work to employees of the manufacturers, who it nominates as Designated Engineering Representatives (DERs) [44, 45]. In aviation this self-regulation is considered satisfactory because major manufacturers such as Boeing and Airbus have a high reputational stake in preventing high profile accidents; any accidents that do occur are intensely studied with remedies applied, and airliner technologies have typically only seen gradual, incremental improvements from one generation to the next.

Structural engineering provides another potential model. The work of structural engineers is not typically subject to detailed regulatory checks; rather structural engineers are trusted to be competent professionals. It is thus the people who are regulated, and not their work. This regulation takes the form of effective self-regulation based around the accreditation of structural engineering as a profession. Although the specifics vary between jurisdictions, this accreditation of structural engineers typically involves two components: education and experience. If a structural engineer is judged to have completed the requisite educational qualifications and accrued sufficient relevant experience, then they are deemed competent by virtue of the resulting accreditation, and this means that they can practise their profession in that jurisdiction. In many jurisdictions there may also be a requirement for continuing professional development.

Fire safety engineers could be (and indeed in some jurisdictions are) accorded the same status as self-regulating competent professionals; in the UK for example a significant step towards this came in 1996 when the Institution of Fire Engineers (IFE) was licensed by the UK Engineering Council to register members with the appropriate professional status according to their educational and experiential standing [46]. However, a number of factors may explain why regulation continues to remain focussed on the quality of fire safety projects rather than on the formal accreditation of the engineers responsible for them. Not only is fire engineering a less mature profession than structural engineering, but also its potential failures may be less visible, and thus provide less feedback, both as regards identifying the individuals responsible and in terms of informing the profession as a whole. Significant fires are (thankfully) rare and may be poorly interrogated to gain useful engineering design feedback, and so fire safety engineering features may lie dormant throughout the whole lifetime of a building and possibly be overlooked even when a fire occurs, whereas deficiencies in structural engineering are likely to be exposed (unless they relate to low probability events such as severe seismic or terrorist events).

3.6 Regulatory expertise and PBD

In any case, whatever the merits of further professionalization of fire safety engineering, the current situation is that regulators typically continue to evaluate fire safety designs. That being the case, the increasing use of performance based fire safety solutions raises two pertinent challenges for regulatory oversight: (1) whether some jurisdictions have enabled performance based design in such a way as to allow too much discretion for local negotiation about what level of ‘safety’ is considered adequate; and (2) whether approvers (or other design stakeholders) have sufficient expertise to assess the merits of fire engineering designs.

On the first point, traditional prescriptive building regulations could be seen as reflecting the ‘revealed preferences’ of society in that they are the cumulative result of local governance, reflecting what was considered acceptable in any particular jurisdiction and reasonable given engineering practice, albeit influenced by commercial and other interests [20]. The guidance that underpins these regulations is couched in quantitative (although not necessarily unproblematic) requirements. However, the shift towards performance based design solutions has in some cases replaced such quantitative guidelines with more qualitative or negotiable judgements about what constitutes a 'satisfactory' or 'adequate' (two common words used in legislation) level of performance.

For example, the performance based design option outlined in the US National Fire Protection Life Safety Code NFPA101 has previously been criticized because:

> … the scenarios and supporting performance clauses of the code are very qualitative in nature and do not provide quantitative advice about the design fire, acceptance criteria, or methodology but simply outline all the factors that should be considered by a designer without actually quantifying any of the necessary input parameters or acceptance criteria. This leaves the designer having to develop their own criteria and design input with the approval of the authority having jurisdiction (AHJ) [47].

In practice design criteria may be established by direct reference to existing prescriptive regulations, so that performance based solutions are permitted so long as they are seen to achieve the same 'outcome' or 'level' with regard to fire safety. Thus, although UK building regulations ceased to have mandatory prescriptive requirements in 1985, the guidelines (e.g. as contained in Approved Document B) continue to be used by some designers as though they were prescriptive requirements, thus setting a baseline against which the adequacy of engineered (i.e. performance based) fire solutions is sometimes judged.

Likewise, US jurisdictions often require performance based solutions to be judged by comparison against the presumed adequacy of the prescriptive codes, and are sometimes developed using prescriptive assumptions. The IBC explicitly permits 'alternative materials, design and methods of construction and equipment', but requires that these are 'not less than the equivalent of that prescribed' in the code [48]. In other words, fire safety can be achieved by different means than those specified in the codes so long as the same overall level of safety is achieved. However, this approach can be problematic because the prescriptive code requirements may not have been originally developed with any rational quantification of safety levels, thus making such comparisons difficult [49].

This issue has attracted most attention in New Zealand, where a 'perceived deficiency' in the regulatory framework introduced in the early 1990s was 'the lack of clear guidance from the regulator for performance criteria and design fire characteristics and scenarios for use in performance-based design' [50]. In some cases, this left the determination of what counted as 'adequate' safety dependent on local negotiation between designers and the AHJ:

> The parameters used within a performance-based design such as the design scenarios, design fires and acceptance criteria are suggested by the designer with the acceptance of the AHJ, which can lead to inconsistent levels of safety being achieved for the design of similar buildings [45].

As a result of dissatisfaction with its building regulations (partly driven by a nationwide scandal concerning inappropriate construction techniques leading to ‘leaky buildings’), New Zealand introduced a major reform of its building codes in 2013. To reduce the potential for inappropriate and inconsistent outcomes the new regulations specify both the inputs and outputs for performance based design solutions in a more rigidly prescribed framework with specified verification methods [51]. The aim was to reduce reliance on negotiation and judgment, and instead to prescribe a framework for how performance should be judged with measurable outputs based on fire safety science that provide a more ‘consistent level’ of fire safety [52].

However, even with such a partially prescriptive approach there remains in performance based design a fundamental shift in the role of expertise and knowledge claims. Within a traditional prescriptive framework the regulators could reasonably claim (perhaps incorrectly in some cases) that they had the appropriate expertise to adjudicate on how the regulatory guidelines should be implemented. Although there was scope for interpretation, regulation could arguably be done as a ‘box-ticking’ exercise, checking compliance with prescriptive rules rather than the assumptions on which they are based, and carried out by ‘code-checkers’. In a performance based approach regulators are faced with requests to approve fire safety solutions potentially based on complex knowledge claims that are rooted in science.

Regulation of performance based designs thus depends not just on the relationship between the regulator and the regulated, but also on the levels of expertise, competence, and professionalism of those involved. Ideally, regulators should be able to understand the analysis that is used to support the fire safety approach proposed. In some cases the regulators will have sufficient expertise either to review design submissions themselves, or to know that they need outside expertise (i.e. third party review) to help. However, in other cases regulators with limited expertise may insist on adherence to the prescriptive rules so as to remain within their comfort zone, and such an approach can be reinforced if the fire services (who may also be key actors in the approvals process, whether formally or not) also lack sufficient technical expertise and are unwilling or unable to seek external technical advice.

Lack of approver expertise can thus prevent approval of projects with performance based fire safety features, but it could also permit approval of projects that are potentially unsafe. Performance based design enables designers to engineer around traditional regulations, but therefore requires fire safety knowledge to be applied professionally. However, if fire safety engineering is practiced by engineers who are not fire safety experts (that is to say, if professional accreditation and competency awareness is weak) then there is a risk that poor design solutions could be approved if the approver also lacks sufficient expertise. Because fire safety engineering relies on several disciplinary domains (e.g. egress, fire development, structural behaviour), it is also crucial that practitioners do not claim expertise outside of their core competencies.

There are many examples – Stansted Airport to take an early one – where a performance based approach showed that common-sense dissatisfaction with the application of prescriptive regulations could be formalised in convincing scientific terms [53]. Performance based design draws credibility from the way that it uses fire safety knowledge to produce solutions that are scientifically rigorous and based on ‘hard data’. In this way, various challenges and solutions can be quantified and trade-offs can be assessed for a range of potential fire scenarios. However, quantification and calculation, if used without sufficient judgment, can result in a spurious appearance of precision.

Fire safety professionals must therefore look beyond elegant engineering solutions, and beyond the need to gain regulatory approval judged against possibly unquantified performance metrics [8, 54-56]. High levels of professional ethics and competence are essential, precisely because of the limits of fire safety knowledge and the need for judgment in its application. The efficacy of performance based fire safety design solutions thus rests not just on the claim that fire and smoke dynamics, structural outcomes, and human behaviour are sufficiently well understood by the technical community, but also that the specific designers and approvers are interpreting and using this knowledge competently and appropriately. It is thus necessary to look not just at the role of social relations in how fire safety knowledge is used, but also at how ‘the social’ affects the way that knowledge is created and verified.

4.0 PART III: GENERATION AND APPLICATION OF FIRE SAFETY ‘KNOWLEDGE’

4.1 (Regulatory) testing

Considered from a historical viewpoint a *sociology of knowledge* approach cannot help but note that much fire safety knowledge is (quite rightly given the need to reduce fire casualties and damage) the product of pragmatic social requirements rather than ‘pure’ knowledge-seeking. Many fire testing laboratories are direct products of the regulatory process (sometimes established by insurance companies or groups of insurance companies), and their activities are geared towards carrying out standardized compliance testing to *demonstrate* regulatory conformance with prescriptive requirements, rather than specifically to *understand* or to *generate* new knowledge.

For about a century, fire resistance testing has been performed in furnaces using standard temperature-time curves. Calls to standardise such testing came in the 1903 International Fire Prevention Congress in London, where both standards and testing were discussed. Edwin Sachs, chairman of the British Fire Prevention Committee argued that the term ‘fireproof’ – ‘now indiscriminately and often most unsuitably applied to many building materials and systems of building construction’ – should be dropped and replaced by ‘fire-resisting’ which ‘more correctly describes the varying qualities of different materials and systems of construction intended to resist the effect of fire for shorter or longer periods, at high or low temperatures, as the case may be' [57]. Amongst the resolutions agreed by the Congress was one that 'strongly recommends the establishment of testing stations for fire-resisting materials and the adoption of a universally recognized method of testing' [58].

The main US standard ASTM (American Society for Testing and Materials) E119 was introduced in 1918, and has remained substantially the same since then [59, 60]. Other standards (i.e. those used by the Underwriters Laboratories Inc., ISO, and NFPA) are similar in nature. ASTM E119 uses a 'fire of controlled extent and severity' to test the 'performance of walls, columns, floors and other building members under fire exposure conditions', with performance judged by 'the period of resistance to standard exposure before the first critical point in behavior is observed' [61]. The purpose of such tests is to determine how long materials or components will maintain desirable properties such as load bearing, integrity, and insulation when subjected to the standard rate of furnace temperature increase.

The results of such tests have become a key part of building regulation and design. Regulations specify, and building control requires, materials or components with ratings of 90 minutes, 120 minutes, and so on. These performance ratings are determined by controlled tests. For example, in ASTM E119: 'The test method prescribed by the standard exposes a specimen (representative of the intended construction) to a controlled fire to achieve specific temperatures over a specific period' [62].

Standardised tests for fire resistance (and other key properties such as flammability, flame spread, etc.) have played an important role in the history of fire safety because they enabled materials and structures to be assessed against simple failure criteria and rated comparatively in a way that matched the requirements of prescriptive regulation. For example, crude measures of fire resistance, such as party walls needing to be two bricks thick (as set out in the regulations that resulted from the Great Fire of London), could be quantified into more comparable measures, such as 120 minutes of fire resistance.

Thus calibrated, performance ratings derived from standard testing provided a rough functional equivalence metric, and complemented regulation based on prescriptive requirements derived from historical events. So long as buildings remained more or less the same with only incremental changes then prescriptive requirements that specified performance based on standard testing may have been able to provide adequate safety. However, the limitations of such standard testing could matter greatly in the context of performance based designs, where claims about fundamental fire safety knowledge are used to create engineering solutions with potentially finer margins of safety; and where innovation in materials and architecture leads to designs that might lie outside the limits of historical 'evidence' of acceptable performance.

One concern with this approach, which is also seen in various other technical fields when they are examined using a sociology of knowledge approach, is that some actors involved in fire safety may take the results of standardized testing to reflect actual performance in fire. Fire test results have become a useful social convention and are central to the building approvals process, and their everyday repetition gives them credibility as representing reality, even though expert opinion has repeatedly noted that this is not the case and was not what the tests intended. For example, in 1970 Harmathy wrote that 'it always must be borne in mind that in a strict sense standard fire endurance is not a measure of the actual performance of an element in fire, and, furthermore, that it is not even a perfect measure for comparison' [63]. In 1981 Law wrote that: 'The standard temperature-time curve is not representative of a real fire in a real building – indeed it is physically unrealistic and actually contradicts knowledge from fire dynamics' [64].

The difference between the standard tests and real fires is only one problematic aspect of testing. There are also questions to be raised about whether the test specimens are sufficiently representative of those that will be used in buildings, either because the manufacturer has given unusual care to the installation of the tested item, or because the test design is unrepresentative of the way that the item will function or perform in real life.

Comparative fire testing for regulatory compliance will no doubt continue to have an important role in standard construction projects that follow prescriptive guidelines. However, it would be less open to misinterpretation if performance levels were rated according to physical behaviour rather than numbers of minutes. There is thus a need to complement (and perhaps eventually supplant) regulatory compliance testing with more realistic testing aimed at characterizing the properties of materials and structures rather than rating them [65]. In the absence of other available approaches engineers are sometimes forced to put forward performance based solutions that specify component ratings such as fire resistance as derived from standard testing as though these reflect true performance. The problem is partly that the performance based approach 'requires engineering data that existing test methods… are not currently configured to provide' [66], and also that the realism (or lack thereof) of standardised component testing may not be properly understood by all fire safety design stakeholders.

Despite the sophisticated tools available for fire safety engineering, in some cases it could be questioned how much the fundamentals have advanced in recent decades. Not only is much of the knowledge used in some aspects of fire safety design largely dependent on regulatory testing, but also the design fires used as the starting point for testing and analysis are often algorithmic simplifications that represented adequate inputs to simple models, but for ease of use rather than realism, and that may be inappropriate for more complex or refined models.

Although fire safety engineers understandably want usable tools that are good enough, rather than excessively detailed, research on the fundamentals is important because in some cases it may not be known how to define or indeed measure what it means to be ‘good enough’. To date, much of the ‘basic’ research at universities and non-commercial government research establishments has been sponsored by industry, and geared towards meeting regulatory testing procedures and norms. Traditional fire resistance testing, or other standards such as the more recent Eurocodes [67] for fire engineering design, define the epistemological landscape around which many research hypotheses are framed. While not losing sight of the pragmatic requirements of the professional world, there is a need for knowledge that is untainted by regulatory requirements. Ironically, such knowledge could help to build confidence in regulatory practices.

4.2 First principles fire science and engineering

Traditional fire safety engineering rested heavily on empirical observation, either from real fires or from testing. Data collected enabled inductive inference by which specific evidence from one event could be claimed to have general applicability. For example, the regulations resulting from the Great Fire of London rested on judgments that the severity of the fire observed was due to the widespread use of wood, the lack of fire resistant party walls, too narrow streets, and so on [68].

Over subsequent centuries the evidence from real fires was supplemented by increasing use of testing. However, understanding of many fundamental processes was lacking, and a prescriptive regulatory approach based at least partly on direct experience of fire disasters had obvious short-fallings if innovation in building materials (e.g. plastics and other oil-based materials) called into question the validity of much of that experience. Rasbash acknowledged this problem in 1974:

> … we cannot continue to rely on the time honoured method of the past in dealing with fire safety, i.e. to rely on experience painfully built up and the passage of decades, if not millennia, for lessons to be learned, sink in and acted upon. Direct experience is becoming too painful a teacher and we must ~~marshall~~marshal our forces to avoid it, if only because of the extensive investments and commitments that might be involved before a tell-tale incident occurs and is recognised, and the trauma of putting things right afterwards [69].

The solution was to improve theoretical understanding so that potential fire safety problems could be predicted from first principles. Such a usable fire safety science rested on the increasing ability to understand and model key processes. As Emmons put it: ‘By the middle of the 20th century, the classical dynamics, the classical quantum chemistry, and the computing machinery had all progressed to the point that solutions of the simpler problems of fire science first became possible’ [70].

This theoretical work was pioneered by figures (to mention a few among many) such as Thomas and Rasbash at the Fire Research Station (now BRE) in the UK, Emmons at Harvard, Pettersson in Sweden, and Kawagoe at the Japanese Building Research Institute. Academics drawing on this early work produced notable textbooks such as *An Introduction to Fire Dynamics* [71], and *Principles of Fire Behaviour* [72]. And building on these advances in underlying science, the availability of sufficient computing power over the last few decades has made the use of Computational Fluid Dynamics (CFD) and Finite Element Modelling (FEM) increasingly popular both for research and as practical design tools for engineers.

In particular, the move towards to performance based design rests partly on a claim that fire safety knowledge is sufficiently advanced to enable deterministic or quantifiable stochastic modelling of fire behaviour and its effects on structures. Advances in CFD have led to a number of models that can now be used to predict fire and smoke behaviour. These models are based on fundamental physical understanding but rest on a large number of assumptions that may be opaque to unskilled users.

However, because of the limited data available from realistic fire tests, much of the real-world validation of these models has depended on data that has been collected either through regulatory testing methods (widely acknowledged as unrealistic in some respects) or, where fire safety research is independent of regulatory drivers, small scale laboratory tests. Laboratory testing can be done in ways that emphasise knowledge rather than regulatory conformance, but there is still ‘difficulty in extrapolating data from bench scale type tests to large scale events’ [73]; large-scale tests are rare because they are difficult and expensive to perform.

Amongst the most significant of large-scale tests were those carried out at Cardington in the 1990s [74]. These were made possible by financial support from the steel industry, and originated partly due to a serendipitous observation of a real fire at an uncompleted fourteen-storey building at Broadgate, London on June 23, 1990. The Broadgate steel structure was only partially fire-protected at the time of the fire, but even though the fire burned for several hours and reached temperatures exceeding 1000°C, no collapse of the structure was observed [75].

Prior to Broadgate, the regulatory approach to the use of steel (based on furnace tests) was to protect (insulate) steel elements of a building so that their temperature would not exceed a certain value, typically about 550°C, in a fire. To achieve this, passive protection needed to be employed to protect the steel, and this added to construction schedules and costs [76]. The Cardington tests provided crucial evidence for the use of performance based structural fire safety design approaches because it enabled the interrogation of the structural performance of specific structural designs in credible fire scenarios, thus facilitating innovative architecture, and also making steel buildings more economically competitive.

Although the Cardington study was generally taken to show that steel did not require the levels of fire protection enshrined in prescriptive regulations, the response of steel structures in fires remains incompletely understood. Despite major advances in both understanding and capability, a 2007 survey noted:

> The general conclusion that can be made from this work at this stage of research in structural fire engineering, the behavior (temperature, strength, failure) of a structural steel beam in natural fire conditions cannot be fully predicted by the calculated methods provided in the literature [77].

Another recent large-scale fire test provided evidence of the limited predictive power of CFD models (or perhaps of CFD model *users*) as regards fire growth in a compartment [78]. In 2006 a series of tests was performed in an unoccupied, and soon to be demolished, tower block in Dalmarnock, Glasgow. Two flats were instrumented, furnished realistically, and then fires initiated. In one (Fire Test One) the fire was allowed to progress to post-flashover, whereas the other involved earlier intervention. A particularly interesting aspect of these tests was that seven different research groups were all given the same starting conditions for Fire Test One and asked to blindly model its subsequent behaviour. The results varied widely. When looking at the Heat Release Rate (HRR) for instance, one simulation provided ‘a reasonably good prediction’, with another 100% over, and the rest under-predicting the HRR ‘in the range of 30-90%’ [78]. It was concluded that ‘current modelling cannot provide good predictions of HRR evolution (i.e. fire growth) in realistic complex scenarios’ [63]. Doubts about the consistency of results obtained by CFD model users were also highlighted by a recent round-robin exercise carried out at Lund University [79].

One might therefore ask whether the future predicted by Emmons [70] has been realised. In 1984, but writing as if from around 2250, he noted that: ‘The first *performance* fire codes were not enacted until the year 2000 which was as soon as the knowledge of fire and the accumulated empirical fire data made general building fire predictions sufficiently accurate’ [70]. There is no doubt that fire safety science has made considerable progress over the last half century. Whether predictions based on this science are ‘sufficiently accurate’ for engineering purposes is a matter of judgment, depending on the context, the extent to which safety margins are applied, and the specific phenomena in question. Moreover, the ability to make good judgments about predictive reliability depends on good understanding of both the strengths and weaknesses of the underlying science.

A potential concern here is that social distance from the process of knowledge production may actually increase belief in the reliability of that knowledge. Other social studies of technology have suggested a phenomenon described as the ‘uncertainty trough’ in which users of a technology may be more convinced of its reliability than the technology’s creators (or the more distanced public on which the technology impacts) [80]. Thus, those who build CFD software tools, and who have done the research that underlies them, are likely to have more limited confidence in their predictive ability than those who use and experience these models in the building approvals process. Although the evidence is anecdotal, there is a concern (within various engineering professions, including fire safety) that the visual outputs of simulation models may have improved out of proportion with the quality of the physics underlying the models themselves. Practitioners (and approvers) may be impressed, for example, by the apparent ability to model the movement of fire and smoke through a building, without fully understanding the assumptions and limitations of the models that generated the outputs.

In addition to the uncertainties associated with understanding how fire and smoke spread, and how buildings respond to fire, there is the considerable challenge of predicting how people behave. Human behaviour, particularly as regards evacuation of buildings, can be modelled, but there is a divergence of opinion about some of the assumptions underpinning these models, and particularly about the quantity and quality of the empirical data on which such models are based [81]. The extent to which evacuation models can provide a quantified representation of what would actually happen in a fire remains somewhat unknown; as a recent survey of evacuation modelling of high-rise buildings noted, 'few validation studies have been performed, mainly because of the lack of real world data available' [82]. It is clear that, whilst massive progress has been made in all of these areas in recent decades, a great deal of further research and education is needed.

Thus, all areas of knowledge that are central to fire safety engineering are characterized by what have previously (and infamously) been termed 'known unknowns', but it is not clear that all practitioners are fully aware of, or reflexive about, the limitations of their understanding. Moreover, there are undoubtedly some 'unknown unknowns', and while these are by definition unpredictable, the potential for unforeseen fire safety failures should (and in many cases does) give pause for reflection. Although in many respects fire safety knowledge has improved greatly over the last few decades, it remains imperfect, constructed not from purely objective facts but rather from the collective judgments of experts from a range of disciplines working in particular organizational, commercial, and political contexts.

5.0 CONCLUSION: THE LIMITS OF SCIENCE AND ENGINEERING

Fire safety has come a long way in the last fifty years. Advances have been made in understanding many of the fundamental processes of fire and smoke dynamics, as well as the structural responses of buildings to fire, and fire safety engineering has emerged as a unique, specialist profession. Thanks to improved knowledge, better engineering, and appropriate regulations, fire deaths are at their lowest level in living memory in many parts of the world. However, it is important not to be complacent, and not only because many other regions still suffer from comparatively poor levels of fire safety. Even where fire deaths are low, and where there appears to be little societal demand for improvement, it is important to be aware of the risks as well as the benefits that come with innovation in both technology and regulatory practices. New materials and building techniques, along with societal changes, can create new challenges and – as New Zealand's 'leaky buildings' episode shows – regulatory innovation can misfire [83].

This paper has highlighted a range of sociological issues related to fire safety, some of which can be considered as 'classical' sociological issues, such as the factors associated with the social context and socio-economic determinants of fire safety risks, and human response to fires. However, the main focus of this paper follows a 'sociology of knowledge' approach that seeks to unpick the processes by which fire safety knowledge is generated and used by the fire safety professions to ameliorate outcomes when unwanted fires do occur. This is a central concern for fire safety engineering because the profession draws on disparate sources of knowledge. Evidence can be gleaned from population-wide statistics that show correlations; from investigations of major fires that are seen to reveal specific deficiencies; from laboratory experiments and a few large-scale tests that are necessarily unlike 'real' fires; and from first principles calculations and simulations. Best practice in terms of knowledge and its application is thus a social construct comprising the latest consensus view of the fire safety community, amalgamating knowledge across different technical domains, and which not only evolves over time, but may also vary according to local practices and whom is considered a qualified member of that community.

The application of improved fire safety knowledge in performance based approaches to fire safety engineering poses particular challenges for regulatory mechanisms. There is the issue of whether regulators can be expected to have sufficient understanding to appraise proposed fire safety solutions, or whether fire safety engineers should more actively seek the status of a profession that regulates its own performance. Either way, there is a need for quantifiable knowledge claims about fire safety performance so that fire safety engineers can confidently justify design decisions, and, in cases where things go wrong, be held to account.

At present what is called performance based design covers a variety of activities, sometimes carried out in a piecemeal manner in a regulatory environment that (in many jurisdictions) remains largely prescriptive in practice (despite the theoretical freedom stated in written regulations). A key requirement for the more thorough-going application of first principles fire engineering solutions is a knowledge base untainted by reliance on regulatory testing, and a widely-accepted methodology for translating societal expectations of fire safety into quantitative measures of adequacy.

However, there may also be cause for concern if the underlying philosophy of performance based solutions imbues undue confidence in 'efficient' engineering solutions. Although the coarse requirements of prescriptive design rules may have led to complicated or unscientific rules that inhibit innovation, it is generally assumed that in most cases they embody a considerable margin of safety.

Replacing this prescriptive approach with fire engineering based on the rational use of the latest scientific knowledge offers considerable benefits, but might also create risks if the resulting fire safety solutions are too finely tuned or poorly regulated. The result may be that some fire engineered solutions are not robust in the face of the practicalities of what happens during the construction and life-time use of buildings.

This paper suggests that there is the potential for further improvement in this field – despite comparatively small losses and a low societal perception of fire risk – and that these improvements are best addressed if social and technical variables are considered together. Fire safety science and engineering ought to be, simultaneously, both more and less social. On the one hand, the great significance that human behaviour has for the use and up-keep of fire safety features points to the need for research that considers how to ensure that buildings are constructed, used, and maintained in a manner intended by their designers – or perhaps to ensure that they are designed in such a way as to make their use and maintenance requirements realistic given social interactions with fire safety technology.

On the other hand, there is also a need for 'pure' basic research, unpolluted by regulatory devices such as the standard fire tests and compliance testing, to further develop the scientific knowledge and engineering tools necessary to design a fire-safe built environment to achieve quantified and agreed levels of performance. Finally, there is a need to quantify the socially acceptable 'levels' of safety across building types and occupancies, such that both the core science and the social application of fire safety knowledge can be directed to achieving the best possible outcomes.

ACKNOWLEDGEMENTS

Many of the ideas leading to this paper originated from The 2013 Lloyd's Register Foundation Global Technical Leadership Seminar in Fire Safety Engineering, held in Gullane, Scotland. The Seminar was majority funded by The Lloyd's Register Foundation (LRF). The authors would like to acknowledge the intellectual contributions the Seminar participants, as well as the in-kind support provided by their respective organizations in allowing them to attend. We are grateful for the support of The Royal Academy of Engineering.

REFERENCES

[1] FEMA (2011) Fire Death Rate Trends: An International Perspective, Topical Fire Report Series, 12(8), https://www.usfa.fema.gov/downloads/pdf/statistics/v12i8.pdf Accessed 12 June 2016

[2] Bijker W, Hughes T, Pinch T (eds.) (1988) The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology, Cambridge MA: MIT Press

[3] Bijker W, Law J (eds.) (1992) Shaping Technology/Building Society, Cambridge MA: MIT Press

[4] MacKenzie D, Wajcman J (eds.) (2nd ed., 1999) The Social Shaping of Technology, Buckingham: Open University Press (1st edition 1985)

[5] Latour B, Woolgar S (1986(1979)). Laboratory Life: The Construction of Scientific Facts. Princeton, NJ: Princeton University Press

[6] Barnes B, Bloor D, Henry J (1996) Scientific Knowledge: A Sociological Analysis, Athlone and Chicago University Press

[7] Collins H, Pinch T (2014) The Golem at large: What you should know about technology, Cambridge University Press

[8] Bullock M, Monaghan A (2014) The Development of Competency in Fire Engineering, International Fire Professional 7:14-17

[9] Jennings CR (1999) Socioeconomic Characteristics and their Relationship to Fire Incidence: A Review of the Literature. Fire Tech 35(1):7-34

[10] Department for Communities and Local Government (2012) Fire Statistics Great Britain April 2013 to March 2014. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/456652/Fire_Statistics_Great_Britain_2013-14___PDF_Version_.pdf Accessed 4 November 2015

[11] Department of Transport (2014) Reported Road Casualties in Great Britain: Main Results 2014. https://www.gov.uk/government/statistics/reported-road-casualties-in-great-britain-main-results-2014 Accessed 4 Jan 2016

[12] The Scottish Government (2012) Fire Statistics Scotland, 2011-12. http://www.scotland.gov.uk/Resource/0040/00403593.pdf. Accessed 15 September 2014

[13] Ahrens M (2014) Smoke Alarms in US Home Fires. National Fire Protection Association, Quincy, MA, USA

[14] Haynes Hylton JG (2015) Fire Loss in the United States During 2014. National Fire Protection Association, Quincy, MA, USA

[15] Federal Emergency Management Agency (1997) Socioeconomic Factors and the Incidence of Fire. Federal Emergency Management Agency, USA

[16] Neavling S (2013) As Detroit breaks down, scourge of arson burns out of control. Reuters (July 13 2013)

[17] http://www.clevelandfire.gov.uk/news-and-events/campaigns/arson-prevention/. Accessed 21 August 2013

[18] Palmer EJ, Caulfield LS, Hollin CR (2007) Interventions with Arsonists and Young Fire Setters: A Survey of the National Picture in England and Wales'. Legal and Criminological Psychology 12:101-116

[19] Wolski A, Dembsey NA, Meacham BJ (2000) Accommodating perceptions of risk in performance-based building fire safety code development. Fire Safety Journal 34(3):297-309

[20] Meacham BJ (2010) Risk-informed performance-based approach to building regulation. Journal of Risk Research, 13(7):877-893

[21] Health & Safety Executive (1988) The Tolerability of Risk from Nuclear Power Stations, London: HMSO, (revised 1992)

[22] Fraser-Mitchell J, Williams C (2012) Cost benefit analysis of residential sprinklers for Wales – Report of cost benefit analysis, BRE Global, 27 April

[23] Roberts H, Curtis K, Liabo K, Rowland D, DiGuiseppi C, Roberts I (2004) Putting Public Health Evidence into Practice: Increasing the Prevalence of Working Smoke Alarms in Disadvantaged Inner City Housing. J of Epidemical Community Health 58:280-285

[24] Duncan C, Wade C (2011) Cost-Effective Domestic Fire Sprinkler Systems. BRANZ Conference Paper 91, Presented at the CIB World Building Congress

[25] UK National Archives file SP 9/171

[26] Ross L (2012) Invitation and Escape: Technical Standards and Tacit Knowledge in the Design Studio. In E. de Vos (ed.) Theory by Design: Architectural Research made Explicit in the Design Teaching Studio. ASP, Antwerp, Belgium

[27] Cullen WD (1990) The public inquiry into the Piper Alpha disaster. HM Stationery Office, London, UK

[28] Fennell D (1988). Investigation into the King's Cross Underground Fire. Department of Transport, London, UK

[29] The Stationery Office Limited (2010) Schedule 1, Part 2 of Building and Buildings, England and Wales, The Building Regulations, UK http://www.legislation.gov.uk/uksi/2010/2214/pdfs/uksi_20102214_en.pdf Accessed 4th January 2016

[30] Hansen G, Condon E (1989) Denial of Disaster. Cameron & Company, San Francisco, USA

[31] Branner JC (1913) Earthquakes and Structural Engineering. The Bulletin of the Seismological Society of America, 3(1):1-5

[32] Fradkin PL (2005) The Great Earthquake and Firestorms of 1906: How San Francisco Nearly Destroyed Itself, University of California Press, p. 244

[33] Drysdale D (2010) The Origins of Fire Safety Engineering in the UK. http://www.see.ed.ac.uk/FIRESEAT/files10/Slides_FIRESEAT2010_Drysdale.pdf. Accessed 15 September 2014

[34] International Civil Aviation Organization (2001) Annex 13 To the Convention on International Civil Aviation Aircraft Accident and Incident Investigation http://www.emsa.europa.eu/retro/Docs/marine_casualties/annex_13.pdf

[35] Caird RG (1996) Fire Safety Engineering: Role in Performance-Based Codes, 3rd Asia-Oceania Symposium on Fire Science and Technology

[36] Meacham BJ (1996) The Evolution of Performance-Based Codes and Fire Safety Design Methods. National Institute of Standards and Technology. http://fire.nist.gov/bfrlpubs/fire98/PDF/f98125.pdf. Accessed 15 September 2014

[37] Department of Communities and Local Government (2010) Approved Document B, Building Regulations 2010. HM Government, London, UK

[38] Law M, Beever P (1995) Magic Numbers and Golden Rules. Fire Technology 31(1):77-83

[39] Albano JM, Fitzgerald L, Meacham BJ (2006) Performance-Based Structural Fire Safety. Journal of Performance of Constructed Facilities 20(1):45-53

[40] Meacham BJ, Bowen R, Traw J, Moore A (2005) Performance-based building regulation: current situation and future needs. Building Research & Information 33(2):91-106

[41] May PJ (2007) Regulatory regimes and accountability. Regulation & Governance 1:8–26

[42] Alvarez A, Meacham BJ, Dembsey NA, Thomas JR (2013) Twenty years of performance based fire protection design: challenges faced and a look ahead. Journal of Fire Protection Engineering 23(4):249-276

[43] Lewis K (2004) A world apart? http://www.building.co.uk/Story.aspx?storyCode=3042560. Accessed 20 December 2014

[44] Downer J (2010) Trust and Technology: The Social Foundations of Aviation Regulation. British J of Sociology 61(1):83-106

[45] Downer J (2011) On Audits and Airplanes: Redundancy and Reliability-assessment in High Technologies. Accounting, Organizations & Society 36:269-283

[46] Bullock M, Monaghan A (2012) The Development of Competency in Fire Engineering. International Fire Professional 2012(7):14-17

[47] Fleischmann CM (2011) Is Prescription the Future of Performance-Based Design? Fire Safety Science 10:77-94

[48] International Code Council (2015) International Building Code. Available at http://codes.iccsafe.org/app/book/content/2015-I-Codes/2015%20IBC%20HTML/Chapter%201.html

[49] Ferreira MJ, Rosenbaum ER, Ballard MS, Schultheis B (2002) UBC Section 905.0 – Smoke Control, A Case Study of the Implementation of Performance-Based Building Codes in the United States, 4th International Conference on Performance-Based Codes and Fire Safety

[50] Wade C, Beever P, Fleischmann CM, Lester J, Llyodd D, Moule A, Saunders N, Thorby P (2007) Developing Fire Performance Criteria for New Zealand's Performance Based Building Code, Paper presented at the Fire Safety Engineering International Seminar, 26-27 April, Paris, France. http://www.branz.co.nz/cms_show_download.php?id=f8f5f396ba47ccae10e62e5c335d917d4d9301c0 Accessed 14 September 2014

[51] Ministry of Business, Innovation & Employment (2013) C/VM2, Verification Method: Framework for Fire Safety Design

[52] Beever P (2013) Presentation at the Lloyd's Register Foundation/University of Edinburgh Seminar in Fire Safety Engineering, Gullane, Scotland, 30 April 2013

[53] Davies C (1991) May: How it was built, The Architectural Review, 21 April

[54] Bullock M, Monaghan A (2014) Code Compliance or Fire Engineering for Safety Design – Have we Moved on? International Fire Professional 8:25-28

[55] Bullock M, Monaghan A (2014) Shouldering the Responsibility International Fire Professional 9:29-32

[56] Bullock M, Monaghan A (2014) Have you got the time? International Fire Professional 10:33-36

[57] Sachs EO (1903) Suggested Standards of Fire Resistance. In Ira H. Woolson ed., Report of the Proceedings of the International Fire Protection Congress, 243-248

[58] Woolson IH (1903) Report of the Proceedings of the International Fire Protection Congress. London, UK

[59] Babrauskas V, Williamson RB (1978) The Historical Basis of Fire Resistance Testing – Part I. Fire Technology 14(3):184-194

[60] Babrauskas V, Williamson RB (1978) The Historical Basis of Fire Resistance Testing – Part II. Fire Technology 14(4):304-316

[61] Wessel R, Gardner M (2004) What do Fire Resistance Ratings Really Mean? The Construction Specifier, January:46-52

[62] Rakic J (2014) Understanding Fire Ratings. http://www.pfpa.com.au/docs/Fire%20ratings/rakic_understanding_fire_ratings.pdf?phpMyAdmin=ZlesLyIQHdlTOtrt-8XBatCVvU6. Accessed 14 September 2014

[63] Harmathy TZ, Lie TT (1970) Fire Test Standard in the Light of Fire Research, Fire Test Performance – ASTM STP 464. American Society for Testing and Materials, Philadelphia, USA

[64] Law M (1981) Designing fire safety for steel – recent work. Proceedings of the ASCE Spring Convention. American Society of Civil Engineers, New York, USA

[65] Maluk C, Bisby LA, Krajcovic M, Torero JL (2015) The Heat-Transfer Rate Inducing System (H-TRIS) Test Method, submitted March, Fire Safety Journal

[66] Beyler C, Beitel J, Iwankiw N, Lattimer B (2007) Fire Resistance Testing for Performance Based Design of Buildings. National Institute of Standards and Technology, Gaithersburg MD, USA

[67] BS EN 1991-1-2 (2002) Eurocode 1: Actions on structures — Part 1-2: General actions — Actions on structures exposed to fire.

[68] Reddaway TF (1940) The Rebuilding of London after the Great Fire (Jonathan Cape)

[69] Rasbash D (1974) Inaugural Lecture at the University of Edinburgh. Available at https://www.era.lib.ed.ac.uk/handle/1842/5574

[70] Emmons HW (1985) The Further History of Fire Science. Fire Technology 21(3):230-238

[71] Drysdale DD (1985) An Introduction to Fire Dynamics, Wiley

[72] Quintiere JG (1997) Principles of Fire Behaviour, Thomson

[73] Buc EC (2008) Fire Testing and Fire Reality: What do Fire Tests Really Tell us about Materials? http://www.see.ed.ac.uk/FIRESEAT/files08/06-Buc.pdf Accessed 14 September 2014

[74] Lennon T (no date) BRE Cardington Steel Framed Building Fire Tests, The Building Research Establishment, UK, http://data.bre.co.uk/dataset/8296db4d-4a80-4a32-ae09-00821678e6ee/resource/bc6bc291-4ab5-498a-8ee2-8726402f1d21/download/BRE-Cardington-Steel-Framed-Building-Fire-Tests-SM.pdf Accessed 12 June 2016

[75] Lamont S (2001) The Behaviour of Multi-story Composite Steel Framed Structures in Response to Compartment Fires. PhD Thesis, University of Edinburgh, UK

[76] Wang Y, Burgess I, Wald F, Gillie M (2013) Performance-Based Fire Engineering of Structures. CRC Press.

[77] Collette KA (2007) Comparisons of Structural Design Fires. MSc thesis, Worcester Polytechnic Institute, USA

[78] Rein G, Torero JL, Jahn W, Stern-Gottfried J, Ryder NL, Desanghere S, Lazaro M, Mowrer F, Coles A, Joyeux D, Alvear D, Capote JA, Jowsey A, Abecassis-Empis C, Reszka P (2009) Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One. Fire Safety J 44:590-602

[79] Johansson N (2015) ‘User Impact on FDS simulations: Reflections Based on the Results from a Round-Robin Study’ at the SFPE conference, Copenhagen, June 4-5. http://c.ymcdn.com/sites/www.sfpe.org/resource/resmgr/2015_Europe_Presentations/Fri_PM_GS.pdf

[80] MacKenzie D, Rüdig W, Spinardi G (1988) Social Research on Technology and the Policy Agenda: An Example from the Strategic Arms Race. In Brian Elliot (ed.), Technology and Social Process. Edinburgh University Press, Edinburgh UK

[81] Spearpoint M, MacLennan HA (2012) The effect of an ageing and less fit population on the ability of people to egress buildings. Safety Science 50:1675–1684

[82] Ronchi E, Nilsson D (2013) Fire Evacuation in High-Rise Buildings: A Review of Human Behaviour and Modelling Research. Fire Science Reviews 2:7

[83] May PJ (2003) Performance-Based Regulation and Regulatory Regimes: The Saga of Leaky Buildings, Law and Policy, Vol. 25, No. 4, Oct, 381-401