FIRE EFFLUENT, PEOPLE, AND STANDARDS: STANDARDIZATION PHILOSOPHY FOR THE EFFECTS OF FIRE EFFLUENT ON HUMAN TENABILITY[i]

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ABSTRACT

It has been known for decades that people die from inhaling fire gases and that visible smoke presents challenges to people trying to escape from fires in homes, transportation vehicles, and commercial buildings. Within the current decade, there has been an invigorated effort, especially in ISO TC92 SC3, Fire Threat to People and the Environment, to develop a coherent and comprehensive set of fire safety standards and guidance documents for life safety. This paper provides an overview of the broad role of fire effluent (toxic gases, visible smoke, and heat) in affecting life safety. It examines what aspects of fires constitute a risk to survival and what elements should comprise a set of fire safety standards to contain that risk to a level that a jurisdiction decides is desirable. This paper serves as a philosophical preamble to the 2008 Conference on Hazards of Combustion Products.

INTRODUCTION

A Time for Discussion

It has been known for decades that people die from inhaling fire gases and that visible smoke presents challenges to people trying to escape from fires in homes, transportation vehicles, and commercial buildings. Meanwhile, the science of understanding how fires burn and how heat smoke and gases are generated and affect people has progressed substantially in the last half century. For instance, in the 1970s, two Gordon Research Conferences[1] convened world experts in fire science to explore ideas and to further coherent research efforts. The International Symposia on Combustion[2] have long included fire research in these biennial meetings; and more recently, the International Symposia on Fire Safety Science[3] and Interflam[4] have covered the full range of fire safety efforts, from fundamental research to engineering applications. There have been a variety of fire research sessions in broader disciplinary meetings and any number of specialist workshops on specific topics of fire safety.

To this author's knowledge, this conference on Hazards of Combustion Products: Toxicity, Opacity, Corrosivity, and Heat Release is the first international technical conference devoted solely to the multiple hazards of combustion products. It comes at a particularly important time. The principles of facility[ii] design for life safety in fires have reached a degree of maturity. Standards and code

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[ii] In this paper, "facility" includes buildings, transportation vehicles, and any other confined or semi-confined premises that might be at risk from a fire.

provisions for fire detection, suppression and control have similarly become the norm. Real-scale (or nearly real-scale) test methods for the flammability of furnishings and interior finish have been established. In addition, some tests have been developed that measure the burning rate of a small cutting from the finished product. Yet, while there have been numerous small-scale apparatus developed for assessing the generation of heat, toxic gases, and visible or corrosive smoke, these facets of life and property safety have not found widespread inclusion in building and fire codes.

Within the current decade, there has been an invigorated effort in ISO TC92 SC3, Fire Threat to People and the Environment, to develop a coherent and comprehensive set of fire safety standards and guidance documents for life safety.[5] Smaller efforts are ongoing within some national and regional standards bodies. As the family of tenability documents continues to be developed, discussed and balloted, it becomes logical to stop for a moment, take stock of what we know and where we are heading, and share thoughts on how best to apply the resources of scientific research and practical expertise. That will be the legacy of this conference.

Fire Control and Fire Safety

There are multiple possible goals for avoiding and controlling fires. One goal is to maintain a function or mission in the event of a fire. This could involve objectives such as avoiding the loss of life for its own sake. A second goal could be to preserve the capability of a facility, sustaining the ability of key people to perform critical tasks within that facility, or limiting the loss of a community asset. A third goal might be to contain the economic loss from a fire. This could mean limiting the loss of business or avoiding an unacceptable loss of personnel. Further goals might include limiting the costs of recovering from a fire and avoiding blame or even punishment for the fire.

Meeting objectives of these diverse types involves equally diverse tactics. These tactics include taking actions to reduce the likelihood that a fire will start, selecting products[iii] and installing fire control systems to contain the maximum extent of the fire, alerting people early and effectively so that they can leave the hazardous area promptly, making it easier and faster to evacuate the hazardous area, taking measures to keep people away from the fire and its combustion products (the fire effluent), and keeping the effluent away from the people.

Building and fire codes (and the analogs for transportation vehicles) are built on combinations of tactics. This approach reflects recognition that a particular code requirement is not necessarily 100 percent reliable, e.g., an automatic sprinkler system may be under maintenance at the time of the fire. It also reflects that a requirement may not be 100 percent effective, e.g., a one hour fire resistance rating for a partition does not mean that it will resist any fire for a full hour.

To be effective and cost-efficient in addressing particular goals and objectives, it is clear that the goal or objective needs to be clearly stated, with a quantifiable measure of accomplishment. It is also necessary that there be a way of sorting and estimating the value of the tactics that might be implemented, individually and in combination.

This is the role of fire standards. There need to be standards that enable selecting and characterizing possible fire scenarios and fire mitigation tactics, and estimating the effects of the fires on people who might be present. A proper set of standards allows different jurisdictions to have different types of objectives and different values of those objectives, yet have a uniform framework for considering facility designs and specifying contained products. The uniformity of the framework enables manufacturers to design their products to a common set of metrics, enables architects and engineers to design facilities using a common set of tools, enables regulators to check facilities for compliance

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[iii] In this paper, a *material* refers to a relatively uniform solid substance, most commonly a polymer or blend of polymers, that may contain dispersed additives. Examples are a polyurethane foam and a cotton upholstery fabric. A *product* is a commercial entity, which may be composed predominantly of a single material, e.g., a wood bookshelf, or which may be an assembly of materials, e.g., an upholstered chair.

with codes and products for compliance with safety standards, and enables the technical community to focus on developing the science and engineering for a coherent set of guidance documents and standards.

Historically, building and fire codes have cited assorted standards and specified a minimum pass/fail criterion for each standard. The criteria often vary depending on the type of facility being regulated. Such a prescriptive set of standards and criteria comprise the facility design requirements and product specifications that, when summed, result in today's degree of fire survival. A standard and a pass/fail criterion are only infrequently prescribed with the expectation of a precisely quantified benefit. Rather, the standard, to some degree, reflects a part of a fire scenario, and the pass/fail criterion eliminates some products or conditions that are perceived as contributing to the undesirable extent of fire loss.

Over the past two decades, engineered fire safety, alternatively termed performance-based design or objective-based design, has become an accepted tool for meeting chosen fire safety goals. Using a set of calculations, assumptions, and (structural, materials, and flammability) data, one estimates the outcome of a fire and the effects of one or more fire mitigation tactics on that outcome. Tactics and performance data are varied to identify combinations that meet the fire safety goal(s). Presumably, high functionality and low cost of the facility also enter into the selection of a particular approach.

At present, the effects of fire effluent on life safety are not prevalent in either the prescriptive or performance-based design approaches. The emphasis is on keeping the fire small or contained, keeping the facility structure intact, and providing egress paths or refuge areas for the occupants.

This paper serves as a philosophical preamble to the papers that follow, with a focus on consideration of the broad role of fire effluent (toxic gases, visible smoke, and heat) in affecting life safety. The following pages examine what aspects of fires constitute a risk to survival and what should comprise a set of fire safety standards to contain that risk to a level that a jurisdiction decides is desirable. Many of the technical topics are discussed in more depth in other papers in this volume.

WHY DO PEOPLE SUCCOMB TO FIRES?

In general, people who have died in fires fit into three categories.[6] Many were unable to attempt escape because they were asleep, disabled, or confined (e.g., in a hospital bed). Many others tried to escape, but did not have enough time before succumbing to the flames, heat, and/or toxic gases. A third category includes those who intentionally enter a burning building, such as emergency responders or people attempting to save relatives or property.

In the United States, most of the fire fatalities were attributed to smoke inhalation, with smaller fractions attributed to burns.[7] Most U.S. fire deaths occurred in residences[8], although the media headlines are often about fires with large loss of life that have occurred in public facilities.

The ability of people to survive a fire depends on a large number of factors. The first set of these factors involve the severity of the fire conditions, such as:

- The combustible mass present;
- The burning rate of each combustible;
- The proximity of the combustibles to each other, determining the mechanism and rate of flame spread and fire growth;
- The air supply for the fire, and any changes that might occur during the fire (such as the opening of a door);
- The yields of toxic gases, heat, and visible smoke from each combustible, as a function of time;

- The transport of the fire effluent across possible escape paths or into places of refuge; and
- The extent of physical damage (e.g., wall collapse) or structural damage to the facility.

A second set of factors results from the design and condition of the building, such as:

- The dimensions of the space in which the fire is burning;
- The existence and effectiveness of partitions for containing the fire;
- The nature and effectiveness of fire alarms;
- The capacity and availability of the escape routes;
- The complexity and marking of escape routes to clear the fire zone and escape from the building;
- The degree of clutter along the escape routes; and
- The presence and effectiveness of fire controls, e.g., automatic sprinklers.

A third set of factors relate to each individual in the facility, such as:

- The person's proximity to the fire;
- The person's mobility;
- The time a person takes before beginning to move toward safety;
- A person's speed of movement toward safety and the extent to which that movement is constructive;
- The objective of the movement, e.g., personal escape, investigation, child rescue;
- The reaction of each person to the sensory effects of the fire effluent (e.g., reduced visibility, skin burns, eye irritation); and
- The susceptibility of each person to the toxic effects of the fire gases.

The last two of these factors comprise the effects of the fire effluent on people. These effects cover a range of severity and can affect survival in different ways.

The most severe effect of exposure to fire effluent is lethality. This can occur relatively quickly, such as when flames spread into an occupied area. It can also occur as a result of a cumulative exposure to the fire effluent, e.g., inhaling a lethal dose of carbon monoxide over the path taken toward an exit.

Of the sublethal effects of fire effluent, incapacitation is frequently tantamount to lethality. If a person is rendered unable to effect his or her own escape[9], and if the fire and its effluent continue to spread, the person's survival is threatened. Comparison of data from bench-scale incapacitation and lethality experiments indicates that the former results from exposures approximately one-half those that cause death.[10,11]

There are additional effects of fire effluent that can limit the ability to escape, survive, and to continue in good health after a fire. Skin burns can be caused by thermal radiation from flames or hot gases, and hot (especially hot and moist) air can cause skin burns by convection. The pain from burns can slow progress and reduce the quality of decisions made as the person moves. Reduced visibility due to high smoke density along the evacuation paths can slow movement and impair decisions, e.g., whether to evacuate and the choice of escape route. Inhalation of toxic gases, at levels well below those that incapacitate, can cause physical discomfort and decrease mental acuity. Irritation of the eyes and airways from, e.g., acid gases in the fire effluent can slow movement speed and lead to poor decisions. There is a paucity of data on these other sublethal effects, and no ratios to lethal exposures have been derived for them. It is presumed that the exposure ratios that will cause the more subtle effects, such as a decrease in mental acuity, will be smaller than the incapacitation-to-death ratio.

These acute effects are not at all considered in fire hazard evaluations, nor are long-term effects of effluent exposure. An ISO document to summarize the state of quantitative knowledge of the sublethal effects of fire gases is under consideration.

The sensitivity of individuals to these effects will also be varied. While factors that affect sensitivity to individual toxicants have been identified (e.g., poor cardiac health increases the sensitivity to carbon monoxide), the actual sensitivity distribution of people is unknown. In one document, a log-normal distribution has been deemed a reasonable choice.[12]

APPROACHES TO LIFE PRESERVATION IN FIRES

Given the large number of factors that bear on life safety, it should be clear that some form of organized and standardized analysis is needed to estimate the extent to which people are in jeopardy from a fire. It's a complex problem, and a streamlined approach is needed if it is to be practicable.

The approach needs to be capable of implementation by facility designers, product manufacturers, and regulators. The designer must be able to obtain and use information for a tenability assessment in a manner that results in a facility that is assessed as sufficiently safe. Manufacturers need a stable system of test metrics for their products, as well as test performance criteria to which they can design or modify their products. Regulators need to review the analyses that the designer performed and the product data from the manufacturer to ensure that the societal requirements for the designed facility and the commercial products are being met.

It would be simplest to mandate that all fires be small and therefore of low hazard to life, and there are some standards and practices in place that are aimed at just this objective. The United States has a mattress standard that constrains the peak heat release rate to 200 kW.[13] Even combined with the heat release rates from pillows and bedclothes, this will keep most bedroom fires from reaching room flashover. Automatic sprinkler systems are designed to quickly control the size of a fire to a level that is well within the fire suppression capability of the fire service. However, fires in cluttered bedrooms can spread from the bed to other furnishings; and buildings with installed automatic sprinklers have experienced large fires, e.g., when the water supply was interrupted. Thus, tactics for keeping fires small should be part of a general approach, but should not be expected to carry all the responsibility for life safety.

Another simple concept would be to perform a test of each construction and furnishing product and label the product with a toxic potency number (as well as a heat release number, a visible smoke number, and a corrosivity number) based on the test results. However, from the long list of factors that affect product performance in a fire and that ultimately affect the product's contribution to tenability, it should be clear that regulating a product based on its performance in a toxicity test is both insufficient and potentially misleading. A single-test label would provide an unknown degree of safety and have an unknown, but significant effect on the range of products selectable for use.

Some type of hazard or risk analysis is needed. The next section discusses the components of such an analysis, the standards that exist or are under development in ISO TC92 SC3, concepts for streamlining the analysis, and possible standards that are yet to be proposed.

STANDARDS NEEDED TO ENABLE SAFETY REQUIREMENTS

ISO TC92 SC3 and SC4 (Fire Safety Engineering) are currently developing a suite of standards for including tenability in engineered fire safety. Many of the following concepts are derived from those discussions. ISO 19706 provides general guidance on assessing the fire threat to people.[14]

There are too many combinations of products, people, facilities, etc. to allow performing a complete hazard or risk analysis for every situation. Thus, a streamlined set of fire safety standards begins with a set of design fire scenarios, as in ISO/TS 16733.[15] In addition to the characteristics included in this document, the scenarios would also include severe, yet reasonably likely to occur, fires that would generate potentially diverse yields of toxic gases and visible smoke. The key features of these scenarios would then be replicated in a corresponding number of types of real-scale fire tests; a document regarding such tests is under development. In each test, a commercial product would be burned under the appropriate ventilation and thermal conditions. Some tests might burn multiple products to assess any potential synergistic effects on the effluent composition and potency.

The results of such real-scale tests, conducted using, e.g., ISO 9705 [16] and ISO 24473 [17], would serve as references for "calibrating" bench-scale tests. This is necessary, since the number of products and test configurations would overwhelm the capability of fire laboratories to perform real-scale tests and would be prohibitively expensive.

Testing of products would begin with one or more bench-scale tests that burn a representative specimen from the finished product. The specimen would preserve (to some extent) the complexity of composition or inhomogeneity of the whole product, while the combustion would reflect the conditions (such as the radiative field and the equivalence ratio) in the real-scale tests.[18] The performance of specimens from a selected set of products in the bench-scale test(s) would have been validated against the real-scale tests of the whole products to the point of establishing the accuracy of the small-scale test(s). The repeatability and reproducibility of the small-scale test(s) would also be established. ISO TC92 SC3 is currently processing results for the equivalence ratio method in ISO/TS 19700.[19] Additional small-scale devices are described in ISO/TR 16312-2 [20], and a historic view of classical effluent toxic potency testing can be found in the book by Kaplan, Grand, and Hartzell.[21]

True measurement of the toxic potency of fire effluent requires a sensor that reacts to all the important components of the effluent. Testing with people as such a sensor is generally not possible. A variety of laboratory animals have been used for this purpose, although most of the published data are for rats.[11] There are significant limitations to relying on a bioassay. Not all animals react qualitatively to all the toxicants in a manner similar to people, the reactions of the animals may be quantitatively different from the reactions of people, routine animal testing is not favored in a number of jurisdictions, and few fire laboratories are capable of performing these bioassays.

As a result, the research community has developed equations for estimating the toxic potency of fire smoke based on the effects of a small number of gaseous components. Equations for the estimated lethality of toxic gas mixtures on rats and for the estimated incapacitation of people by inhalation of gas mixtures can be found in ISO 13344 [22] and ISO 13571 [12], respectively. (ISO 13571 also contains equations for the incapacitating effects of heat and visible smoke.) ISO 19706 states that incapacitation is the proper toxicological endpoint for use in estimating the available time for escape from a fire. Since the physical incapacitation of rats occurs at effluent exposures of approximately one half those that cause death (for a wide variety of materials and products), the equation in ISO 13344 can readily be adapted to this endpoint.

The use of these equations to represent toxic potency has a significant limitation. If a particular product generated a gas of significant potency that is not in these equations, the potency of the effluent could be seriously underestimated. There have been reports of a small number of materials that did combust to yield such toxicants. Fortunately, the contributions of a small set of toxic gases have been shown to estimate rat lethality within about $\pm$ 20 % for a wide variety of materials and products. Nonetheless, it would be prudent to retain the capability to perform animal check tests when products of non-conventional chemical formulation are under consideration. A standard for identifying these uncommon materials and products is yet to be developed.

Obtaining the input for these equations requires standards for measuring the yields of known toxic gases and visible smoke. ISO 19701[23] describes a wide range of analytical chemical techniques for measuring the concentrations of these gases. ISO 19702[24] guides the use of Fourier Transform infrared spectroscopy for these measurements. ISO 19703[25] contains equations for calculating the yields of the toxicants from the measured concentrations and knowledge of the conditions in the apparatus. Standards are also under development for determining and utilizing the limits of detection of the gases and their limits of quantification. Similar documents for smoke aerosols are also under development.

Even with the refinement of the effluent characterization to a small number of gas and aerosol measurements in a small-scale combustor, it is still not practical to test all products. Once the accuracy, repeatability, and reproducibility of a bench-scale apparatus have been determined, and once toxic potency values for a diversity of products have been measured, guidance for estimating the toxic potency of most future effluents without testing should be feasible. This will require pre-normative work before such a standard can be developed.

Once the yields of toxicants and aerosols have been determined, the next task is to estimate the available safe egress time (ASET). ASET is the time between when the fire starts and incapacitation occurs. As people move along an escape route, they encounter temperatures and concentrations of gases and smoke that vary with time and location. At some time, they reach a level or an accumulation of one of these that result in incapacitation. Equations for these incapacitating levels are found in ISO 13571, as is an introduction to the consideration of protecting people with heightened sensitivity to the components of fire effluent. Examples of the calculation of ASET are to be developed.

For a person to survive a fire, it is generally accepted that the value of ASET should exceed the time required for escape (RSET). RSET includes such factors as the time at which the fire is detected, the time at which the alarm is sounded, the time at which each person begins to move toward an exit, and the speed at which the person proceeds.[26] Sub-incapacitating effects of the fire effluent can influence these, but little information is available to quantify these effects, and a standard for estimating RSET remains to be developed with ISO TC92 SC4.

The comparison of ASET and RSET values indicates whether a person with particular characteristics will escape safely from a particular location in a specific building in which there is a specific fire. By selecting a severe fire and occupants who are very susceptible to fire effluent, it is possible to estimate whether a facility will offer a relatively high degree of fire safety and to specify the products appropriate to construct and furnish such a facility. Such a fire scenario may be so extreme that the functionality of the facility may be low and the cost excessive. Of more use is an estimate of the risk of loss of human tenability. This is obtained by summing over important fire scenarios and occupant characteristics, each weighted by its severity of consequence and likelihood of occurrence. Guidance on the estimation and use of fire risk is provided in ISO/TS 16732.[27] The first set of examples, which do not yet include human tenability estimation, are in development in ISO TC92 SC4.

Finally, there will be a need for a hazard- or risk-based standard for characterizing the contribution of a product to human tenability. Discussions of approaches to such a standard are just underway.[28] Any such approach must not exceed the limited precision of the toxic potency estimates. Such a standard could be applicable whether the objective of the hazard or risk assessment is to maintain the currently experienced level of toxic fire hazard or to decrease the general toxic hazard from the currently experienced level.

WHERE ARE WE?

Subcommittees SC3 and SC4 of ISO TC92, Fire Safety, convene most of the (relatively few) world experts on factors affecting human tenability. Within the last 5 years, the core of a set of standards for the uniform assessment of human tenability in fires has been constructed and successfully balloted. A plan for the remainder is being detailed, and development of some of these documents is already underway.

At present, experts in the field can use the existing Standards, Technical Specifications, and Technical Reports to perform reasonable estimates of human tenability within a burning facility and estimate values of ASET. When the full set of documents is in hand, engineering practitioners around the world will be able to perform and share such analyses. Because the documents describe techniques and do not set facility or product safety compliance criteria, they can be utilized in jurisdictions with different levels of safety requirements.

The fire protection engineering profession is ready to implement a human tenability assessment methodology for building evaluation based on these standards. Many of the principles that are embodied in the current and planned standards have been used in reconstructions of fatal fires, primarily in support of litigation.

The prognosis is less clear for the possible design or selection of construction and furnishing products to achieve a desired (or specified) degree of egress safety. In the simplest of extremes, it might be, e.g., that control of the potency of fire effluent is unimportant or that a small number of products need to be restricted to applications where their mass is a small fraction of the total combustible load. Further research and fire risk calculations are needed to guide any activity. Whatever the outcome, incorporation of the findings into standards will be necessary to guide the marketplace.

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