USE OF COMBUSTION EFFLUENT DATA IN TENABILITY ASSESSMENT[i]

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ABSTRACT

Typical prescriptive and performance-based assessments of life safety in building fires do not explicitly consider the contributions of the toxic potency of combustion gases, smoke obscuration, or the thermal and radiative environment. This paper characterizes two approaches (one rigorous and one simplified) to fire hazard assessment that include the effects on life safety of airborne toxicants, visible smoke, and heat and explores the implications of such methodologies for characterizing the fire performance of construction and furnishing products

INTRODUCTION

There are two broad fire safety objectives for considering the inclusion of toxic potency data (as well as smoke obscuration and heat generation data) in facility designs and usage plans:

1. Quantification of the currently experienced level of toxic fire hazard, leading to maintenance of this level as product technologies and building designs change.
2. Decrease in the general toxic hazard from the currently experienced level.

At present, a typical prescriptive assessment of life safety in a building fire does not explicitly consider the contributions of the toxic potency of combustion gases, smoke obscuration, or the thermal and radiative environment. In some jurisdictions, there are requirements for building products of controlled burning rate and visible smoke generation; and, for some occupancies, there are requirements for furnishings of low heat release rate. However, the sufficiency of emergency egress capability tends to be determined by building parameters, such as the number and width of stairwells, the promptness of fire detection and alarm, and the capacity of smoke venting systems. These building design and system tactics have contributed to improvements in life safety. Nonetheless, inhalation of fire gases continues to be the leading cause of fire deaths, at least in the United States.[1]

As an alternative to compliance with a set of prescriptive code specifications, some jurisdictions permit the submission of a performance-based design 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 performance-based design approaches (except, perhaps, as an indicator that the fire is sufficiently small to achieve the life safety objective). 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.

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This paper characterizes rigorous and simplified approaches to fire hazard assessment that include the effects on life safety of airborne toxicants, visible smoke, and heat and explores the implications of such methodologies for characterizing the fire performance of construction and furnishing products.[ii] Some of the ideas in this paper have emerged from discussions within ISO TC92 (Fire Safety), particularly SC3 (Fire Threat to People and the Environment and SC4 (Fire Safety Engineering), although not necessarily in the format presented here. Guidance on performing a *risk* assessment of a building, which subsumes the elements of hazard assessment, can be found in ISO/TS 16732.[2] Good examples of the relative role of alternative products in risk assessment can be found in Reference 3.

A RIGOROUS APPROACH

The resources and expertise required for this sophisticated and detailed methodology suggest that it would be most likely used, and adapted, for individual buildings[iii] of unusual design, special purpose, or high risk avoidance, rather than applied in routine practice. Experience has shown that this degree of analysis is also used in large litigation cases.

1. The process begins with the choice of a life safety objective. This could include a safe evacuation of the full building or movement of people to areas that are safe from the fire and its effluent. It could include consideration of the need for people to remain in the building to complete critical functions or the possibility that physical damage to the building, e.g., from an earthquake, might make mass movement of people difficult or impossible.
2. The second step is the construction of a description of the building under consideration. The description should include such features as the interior partitions and their expected fire endurance, any air flow paths, such as stairwells and open vent shafts, egress paths, intended places of refuge, etc.
3. The next step is selection of a set of design fires.[45] If the information were available, the set would be based on historically experienced probable fires of serious consequence. The fires would include a range of initiation fire locations, combustibles, mass burning rates, etc. To include effluent effects, the design fires would also need to include severe values of the variables that affect the generation of toxic gases and smoke, including the degree of ventilation for the fire and the chemical composition of the combustibles. Since these two properties can vary during the fire, the use of a commonly used simple quadratic, t^2, curve for fire growth is not likely to be representative. Burn tests of the major combustibles may be necessary if no data are available.
4. Fourth is the characterization of the effects of active intervention, such as the discharge of water from automatic sprinklers. For sprinklers, this would include such factors as the residual burning rate of the fire after water discharge, changes in the combustion products from the wet combustibles, and any change in the flow of visible smoke to locations remote from the fire. The baseline appraisal (e.g., without automatic sprinklers) also provides an indication of the outcome if the sprinklers were not functioning.
5. Next is the quantification of the yields of heat, toxic gases, and visible smoke generated from each combustible. These yield values (quantity generated in the fire divided by the mass of the combustible item consumed) could be obtained from a set of real-scale burn tests, from validated small-scale apparatus[6], or from prior laboratory data for similar

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[ii] 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.

[iii] Although the term "building" is used throughout this paper, the approaches are applicable to any enclosed space, such as a transportation vehicle or a tunnel.

combustibles[7]. Data would be obtained for at least one set of underventilated and one set of well-ventilated fire conditions.

6. Sixth, it would be prudent to estimate the toxic potency from the measured gases (using the equations in ISO 13571[8] and confirm the accuracy of this estimate using an animal check test, as included in NFPA 269.[9] This is especially valuable if the chemical composition of the combustible item is unlike other combustible items that have been examined, or if the chemical and physical composition of the combustible item suggests the potential for the formation of unusual toxicants.

7. Next is the simulation of the design fires, using a validated CFD model, such as the Fire Dynamics Simulator.[10] This moves the toxic gases and smoke around the building, allowing for their deposition on surfaces, and tracking the air temperatures and radiant flux fields throughout the building. The time of alarm would be determined by some pre-specified condition, such as when the level of a detectable effluent component reached a selected value at the site of a sensor. Some simulations might need to be run multiple times if there were the potential for a probabilistic fire-altering event (i.e., an event that the designer does not want to accept as 100 percent assured), such as the opening of a door or window or the activation of automatic sprinklers.

8. Next, people would be placed in various locations, corresponding to their expected places at the start of the fire.

9. The methodology continues with construction of a set of behavioral scenarios for the people, using data from prior studies and information pertinent to the building at hand. These scenarios would include such characteristics as the activities underway when the fire is detected, the physical and mental capabilities of the people, the number density of people in the building, their degree of training in the event of a fire, their sensitivities to smoke and gases, and the presence of staff trained in emergency procedures. A document for constructing such behavioral scenarios is under development in ISO TC92 SC4 WG11, Human Behavior.

10. In the simulations, the people would start moving at appropriate times, taking into account historically determined response to fire alarms and actions prior to beginning movement toward escape or refuge, and at movement speeds consistent with their physical condition.

11. Since few data exist on the effects of heat, visible smoke[11], and toxic gases on movement speed, the next step is estimation of these effects, as well as possible effects of the fire effluent on the quality of any decisions that are needed.

12. The condition of each occupant is monitored as the movement process evolves. This is accomplished using the fractional effective dose (FED) and fractional effective concentration (FEC) equations in ISO 13571 to gauge each person's exposure to fire effluent as they move through the time-varying fire-generated environment.

13. Next is identification of whether and when each person is incapacitated, i.e., unable to effect his/her own escape,[12] and the cause of the incapacitation (radiant heat, convective heat, narcosis, irritation, or loss of visibility), i.e., the limiting hazard. The monitoring is continued after incapacitation to see if other hazards would have incapacitated at about the same time or would have occurred substantially later. This helps focusing the efforts in steps 15 and 16 on changes that would be most effective in increasing tenability following a fire.

14. For a risk analysis[13] (as contrasted with a hazard analysis), the scenarios are weighted by their likelihood of occurrence (if such data exist), and the weighted outcomes of the scenarios are summed. The results are then compared with historical life loss data to determine whether the life safety of the building design is consistent with the general pattern or not.

15. If the purpose of the analysis is an assessment of a building design, adjustments are made to the design, furnishings, air handling, or other parameters; and the simulation is repeated until the finding of one or more designs for which the life safety objective is reached.
16. If the purpose of the analysis is for a party to litigation, the event conditions are varied in a similar manner until one or more sets of conditions lead to the actual (undesired) outcome of the event or how changes to the actual building might have affected the (undesirable) outcome.
17. Sensitivity studies are performed to identify the sensitivity of the simulation outcomes to the input conditions, e.g., effluent yields, sensitivity of the people to the effluent components, movement and behavior characteristics of the people, progress of the fire, etc.

This approach clearly requires extensive data gathering, computer simulation, outcome interpretation, and documentation of the process. Analysis of the safety aspects of a single building could take weeks or months. However, it may be worthwhile for a performance-based design or for demonstrating a level of life safety beyond that required in the building code.

A SIMPLER APPROACH

To be useful for routine analysis, an engineer or architect needs to perform the analysis in a few hours at most. A simpler process is similar to a more rigorous approach, but a number of careful approximations are made. These range from simplifying the building design and the fire description to reducing the complexity of the physical and physiological characteristics of the building occupants. These approximations limit the accuracy, but if done carefully, the analysis may be suitable for identifying undesirable designs.

1. The process begins with the choice of a life safety objective, much the same as in the rigorous approach.
2. The analysis would continue with a selection, from a menu of generic designs, of a building similar to the one under consideration. The description would include interior partitions, but assume, e.g., that they are not breached by the fire before the people are all safe. Air flow paths might be represented by holes, rather than stairwells or utility shafts. Egress paths and intended places of refuge are identified.
3. The small set of design fires might include one underventilated, post-flashover fire of an assemblage of high burning rate combustibles and one smoldering fire.
4. For a smoldering fire, hazardous levels of toxicants and smoke are typically only experienced in the room of fire origin. The yields would be obtained from reference lists. A one-room simulation would be performed, preferably using a CFD model. Fire sensors in the room might activate; automatic sprinklers would not activate, since the temperature rise is very small away from the smoldering.[14]
5. For the post-flashover fire, the generation rates of effluent would be assumed proportional to the mass burning rate, which would be represented by a simple t^2 curve. An initial assumption might be that, given that multiple items might be burning in a fire of high severity, the toxic potency of the smoke would be characterized by an average IC_{50} value[15] or a typical yield of carbon monoxide, multiplied by a small factor to include the presence of other, but secondary toxicants. A second simulation could include effluent of significantly higher toxic potency. The visible smoke yield would come from a table of yields from various combustibles.

   The mass burning rate curve and effluent yields would be input to a validated CFD model, such as the Fire Dynamics Simulator, or a validated zone model, such as CFAST.

For each design fire, the model would move the toxic gases and smoke around the building, allowing for their deposition on surfaces, and tracking the temperature and radiant flux throughout.

Activation of automatic sprinklers would quickly extinguish the simulated fire or control it at a steady, very low burning rate.

6. In both fire scenarios, people would be placed at appropriate locations and would not move. Initially, they would be assumed to be of median sensitivity to the components of the fire effluent. Using the equations in ISO 13571, the simulation would calculate the time at which the fire effluent led to incapacitation at each location and the cause of the incapacitation. The simulation would continue after incapacitation to see if other hazards would have incapacitated at about the same time or would have occurred substantially later. Repeat simulations would be performed for smoke of higher potency or (equivalently) people of higher sensitivity.
7. For the smoldering fire, the time to incapacitation of a person in the fire room would be compared to a reasonable time for rescue by other building occupants or emergency responders. (For those cases where no one is near enough to hear the alarm, only such non-building-related tactics as ignition-resistant furnishings and less fire-prone cigarettes would provide a degree of safety.)
8. For the post-flashover fire, the time required for escape (RSET) would be estimated from the typical times people take before beginning to leave a burning building, an average value of movement speed, and an estimated distance to safety. This would be compared to the estimated times to incapacitation to determine whether people are incapacitated.
9. If the purpose of the analysis is an assessment of a building design, and if the effluent monitoring sites indicate that incapacitation would occur, adjustments would be made to the building design and the t^2 fire growth rate and toxicant yields (through changes in materials or fire control tactics) until the calculate value of ASET exceeded the estimated value of RSET. The results would indicate the extent to which additional constraints are needed if the building is to meet the life safety objective. It is possible that the results would indicate that a more careful analysis is required.

IMPLICATIONS FOR PRODUCT CHARACTERIZATION

To perform fire hazard and risk assessments of a building, it is necessary to have quantitative information on the fire effluent of the potential combustibles. There are already heat release and smoke yield requirements for some types of products in some applications and jurisdictions. Thus, the practicality of selling products with specified maximum values of these two parameters has been established.

However, it is probably not feasible to expect true and precise toxic potency measurements of all building and furnishing products. In their present state, true determinations involve the use of laboratory animals. Such tests are expensive to run, and there are insufficient laboratories to test the tens of thousands of products in the marketplace. In addition, concerns in some countries regarding routine animal testing makes unlikely the advent of regulations suitable for international trade. A number of test apparatus have been designed to measure the yields of known toxic gases[16], and there are empirical equations to use these yields to estimate the toxic potency of the combustion effluent.[8,17] Here again, the sheer number of finished products and the associated cost of testing makes it unlikely that universal testing would occur. Thus, some expedited, but reasonably accurate construct for implementing smoke toxic potency data in a product's fire performance characterization is needed.

A recent paper by this author explored some candidate premises for simplifying both the testing of products and the grouping of products using estimates of their contributions to toxic fire hazard.[18]

- Incapacitation, which stops progress toward escape or seeking refuge, is the most usable marker of a threat to life safety. The use of incapacitation, rather than lethality, is conservative, since it occurs at effluent levels lower than those that cause death directly. The exposures leading to other sublethal effects, such as reduced physical or mental capacity, have not been quantified. Incapacitation is defined as the inability of a person to take action to effect his/her escape from danger to a place of safety. For inhaled gases, this is dose-related for narcotic gases and concentration-related for irritant gases.[8] Another cause of incapacitation is pain from radiative and/or convective heat, while high visual obscuration can effectively incapacitate by eliminating constructive progress toward exits or places of refuge.[8]
- Grouping incapacitating toxic potency values within factors of ten is consistent with the accuracy and precision of the individual values.[iv] The accuracy limit arises from the combined uncertainties in the degree to which the toxicity test apparatus replicates the actual fire conditions of interest, estimation of toxic potency values from chemical analysis of the effluent, extrapolation from the common 30 min rat exposures from which the gas equations are derived to the short (≈ 5 min) exposures in actual fires, and the extrapolation of potency values from rats to people. Thus, the incapacitating toxic potency of "ordinary" combustibles would be in a range between three times a median value and one-third of the median value. A compilation of published data indicated the median IC_{50} value is approximately 11 g/m^3.[15]
- Many combustible finished products are composed of a few common atoms: C, H, O, and N. To the extent that a finished product contains only these atoms, the important toxic combustion gases are few. The polymers in a few products contain additional atoms, e.g., Si and S. Fire retardant additives typically contain atoms of the halogens, phosphorus, boron, and/or a few types of metals. To the extent that these additional atoms are present, there is potential for generation of additional toxic gases (or higher yields of some otherwise less prevalent toxic gases), such as those that result from incomplete combustion of the finished product.
- Most life safety assessments will be for residential or office occupancies, where life loss from smoke inhalation is predominantly from post-flashover fires.[19] After flashover, virtually all the combustibles in the room of fire origin are burning. The fire effluent is the sum of that produced by each of the burning combustibles. The consumed mass flux is high, and the effluent from incidental contributors (those with comparatively small mass present) is rarely important.
- Pre-flashover fires are frequently dominated by a single finished product, such as a chair or a made-up bed. In the early stage of such a fire, the combustion is well-ventilated; in the later stages, vitiation likely gives toxic product yields closer to the values from post-flashover fires.

Given the broad uncertainty in the values of incapacitating toxic potency for people, there were four suggested descriptors for the effluent from finished products:[18]

> Group 1: Distinctly less toxic effluent than that from typical combustibles in all types of fires. There should be few entries in this Group, since carbon monoxide is almost always generated in the combustion.

[iv] Incapacitating toxic potency values derived from the exposure of laboratory animals, generally rodents, typically are expressed as an IC_{50}, the smoke exposure that results in incapacitation (I) on half of the animals. (The toxic potency of the effluent varies inversely with the IC_{50} value. Thus, a low IC_{50} value indicates that it only takes a small exposure to result in incapacitation, and the effluent would be described as having a high toxic potency.) Virtually all published data are for lethality (LC_{50}) and incapacitation (IC_{50}) determined in bench-scale tests using small test specimens.[15] Most of the data are for 30 min exposures, followed by a 14-day post-exposure observation period. Indicative experimental uncertainties in these values are of the order of ± 30 %.

Group 2: Regardless of toxic potency, the product is *never* a significant contributor to toxic fire hazard due to the low mass present. An example is an on/off light switch plate.

Group 3: "Ordinary" contributor to the overall toxic potency, as described above.

Group 4: Significantly more toxic fire effluent than that from typical combustibles. This Group could be further divided into subgroups by factors of ten in toxic potency.

A product described as fitting into Group 1 or Group 2 is not a significant contributor to a *toxic* threat to life safety. (Of course, such products with, e.g., a high mass burning rate can rapidly lead to an untenable *thermal* environment or increase the likelihood of fire spread to additional combustibles, which would generate more, and perhaps more toxic, effluent.) Products that are described as fitting into Group 3 (almost certainly the largest Group) are those products whose fire effluent characterizes the toxic hazard from the range of current conventional fires.

Typically, products that are described as fitting into Group 4 will result in ordinary toxic hazard in some fire situations and will contribute to enhanced toxic hazard in others. *Association with Group 4 is an alert to those performing fire hazard and risk analyses, rather than the basis for outright discrimination in product selection. The products may well have other characteristics that favor their use in some applications.*

The totality of burning products determines the overall smoke composition. Since a manufacturer cannot know the features of the fire in which a product might be involved, an estimation of the potential contribution of the product to toxic hazard could be based on the fire safety objective and the general fire type:

Table 1. Matrix for Appraising the Toxic Fire Hazard of Products.

Objective → **Design Fire ↓**	**Support Maintenance of the Current Level of Toxic Fire Hazard**	**Decrease Toxic Hazard from the Currently Experienced Level**
Pre-flashover fire, single burning product	Group a	Group b
Post-flashover fire, multiple burning products	Group c	Group d

For each of the four combinations of objective and design fire, an appraisal of which of the four Groups in which a product would fit would be estimated using

- The chemical composition of the product,
- An estimated (or measured) toxic potency,
- The mass of the product likely to be used (relative to the total combustible mass involved in a fire that is likely to be life-threatening), and
- The mass burning rate of the product (relative to that of average combustibles in a residential or office building).

A given product might fit in different groups, depending on what else is burning in a particular fire scenario. Since one cannot presume the mix of finished products that will participate in a fire, the characterization of a particular product would be that of the highest numbered Group from the four appraisals. The paper provides some worked examples of the process.[18]

FINAL COMMENTS

Current building design typically achieves a certain degree of life safety in fires through compliance with the provisions of building and fire codes. These codes and current practice do not explicitly include interactions of people with the fire effluent. Providing for fire-people interactions offers the potential for sustaining the current level of fire safety as technologies and products evolve or improving the level of life safety, should society demand it.

There is extensive knowledge of these interactions that has been developed through decades of fire safety and physiological research. It is possible to provide for the effects of toxic gases (as well as heat and smoke obscuration) on people taking actions to save themselves in a fire. Limited data are already available for estimating these effects, and formalizing the analytical process will stimulate greater product fire performance data. It remains to be seen whether life safety analyses are sufficient, given the suggested grouping of smoke toxic potencies in groups that differ by an order of magnitude. It is hoped that this paper and this conference will inspire discussion of, research into, and data for valid life safety analyses that protect the public and promote an orderly marketplace for product manufacturers, building designers, and regulatory officials.

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