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SHORT COMMUNICATION

Hazards of combustion products: Toxicity, opacity, corrosivity, and heat release: The experts' views on capability and issues[‡]

Richard G. Gann[1,*,†], Vytenis Babrauskas[2], Stephen J. Grayson[3] and Nathan D. Marsh[1]

[1]*National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.*
[2]*Fire Science and Technology, Issaquah, WA, U.S.A.*
[3]*Interscience Communications, London, U.K.*

SUMMARY

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. The principles of facility design for life safety in fires have reached a degree of maturity. Standards and code provisions for fire detection, suppression and control have 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 results of the burning of a small sample from the finished product. Yet, while there have been numerous small-scale apparatuses 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. 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. Smaller efforts are ongoing within some national and regional standards bodies. In November 2008, experts in this field gathered at The Royal Society in London to hear papers that captured the state of the art and to discuss where we might go from here. This paper summarizes the papers and the discussion from that meeting. Copyright © 2010 John Wiley & Sons, Ltd.

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1. INTRODUCTION

It has long been known that people die from inhaling fire gases, that fire effluent can damage electrical and mechanical equipment, 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.

On 10 & 11 November 2008, some 90 experts in this field gathered at The Royal Society in London to hear papers that captured the state of the art and to discuss where we might go from here. This was the first international technical conference devoted solely to the multiple hazards of

*Correspondence to: Richard G. Gann, National Institute of Standards and Technology, Gaithersburg, MD, U.S.A.
†E-mail: rggann@nist.gov
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combustion products, and it came at a particularly important time. The principles of facility[§] design for life safety in fires have reached a degree of maturity. Standards and code 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 results of the burning of a small sample from the finished product. Yet, while there have been numerous small-scale apparatuses 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 [1]. 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 became 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.

This paper continues with brief summaries of the presentations at the conference. Then, given this context, we list the key points that resulted from the various discussion periods.

2. THE TECHNICAL PROGRAM

The following is a list of the 23 papers that were presented, along with synopses of their content. A bound book containing the full text of the papers can be obtained from Interscience Communications [2].[¶]

2.1. Toxicity

Fire Effluent, People, and Standards: Standardization Philosophy for the Effects of Fire Effluent on Human Tenability; Richard G. Gann, National Institute of Standards and Technology (NIST), U.S.A.

There are multiple possible goals for avoiding possible fires, and there are a variety of factors that affect the ability of people to survive a fire. These give rise to the need for an organized, standardized, and streamlined analysis for estimating the extent to which people are in jeopardy. ISO TC92 SC3 is developing a suite of standards for including tenability in engineered fire safety. Central to this is the accurate determinations of the yields of toxicants to characterize the time- and space-varying fire environment. This, in turn enables the estimation of the available safe egress time (ASET) and the required safe egress time (RSET). A comparison of these two values indicates the potential for the safety of an individual in the chosen design fire in a given building. The need also exists for a hazard- or risk-based standard for characterizing the contribution of a product to human tenability.

Smoke Toxicity Test Development and Use: Historical Perspectives Relevant to Today's Issues; Gordon E. Hartzell, Hartzell Consulting, Inc., U.S.A.

The pioneering of fire toxicology occurred in the 1950s. Even then, until the 1970s, most fire tests had been developed for the protection of property. In the U.S., growing public awareness of the magnitude of the fire problem and the discovery of the first 'supertoxicant' led to the development of a number of small-scale, animal-based smoke toxicity tests. These tests incorporated a variety of specimen combustion and animal exposure models. The principal uses of these tests were to screen for unusually toxic smoke and to develop prescriptive requirements for materials and products.

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

[¶] The full text of one paper (Assessment of Combustion Product Hazards for Aircraft) was not available at the time that the book went to press. A copy of the visuals from that presentation can be obtained from Interscience Communications.

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Subsequent research led to bases for validating these tests against real-scale fires and consideration of using the test output in engineering models to mitigate fire injuries and deaths. Strategically, this approach is more valid than regulating products solely on the basis of a small-scale test.

Fire Gases and Their Chemical Measurement; *Yannick Le Tallec*, *Centre Technique Industriel de la Construction Metallique* (*CTICM*), *and Eric Guillaume*, *Laboratoire National de Metrologie et d'Essais* (*LNE*), *France*

There are a small number of gases that most commonly determine the acute toxic potency of fire effluent. Combustible gases, gases with environmental and long-term effects, and smoke aerosols may also be of interest. To ensure that the measured concentrations of these species is accurate, one must pay attention to the location and the design of gas sampling probes, any filters inserted in the sampling lines to protect the chemical instrumentation, the materials used in the sampling lines, and the sample pumping rate. The effluent may be sampled continuously or on a batch basis. There are multiple chemical analytical techniques for each of the species. The choice of technique depends on its selectivity and sensitivity, the range of concentration, the limits of detection and quantification, the repeatability and reproducibility, and the accuracy. Each measured value should be presented with an indication of measurement uncertainty.

Fire Models Used in Toxicity Testing; *Eric Guillaume and Carine Chivas*, *Laboratoire National de Metrologie et d'Essais* (*LNE*), *France*

Many physical fire models (i.e. small-scale combustors) have been used to generate effluents, the toxic potency of which could be used for regulation or fire safety engineering analysis. In an ideal physical fire model, the combustion conditions replicate at least one stage of an actual fire, the test specimen is representative of the complete product from which it has been cut, the effluent has been related to the effluent from the burning of the complete products, and the test results are both repeatable and reproducible. The sampling and transport of the effluent, as well as the quality of the chemical analytical instrumentation, affect the ability to determine the accuracy of the model. To date, only limited validation work has been performed, and no model has achieved international consensus. It is likely that there will not be a unique model for each fire stage.

Scaling of Toxic Gas Data; *Per Blomqvist*, *SP Technical Research Institute of Sweden*

Data from which a fire's impact on escaping people can be estimated are necessary for performance-based fire safety engineering. Such data are most likely to come from a bench-scale test, which might be characterized either as closed chamber or as flow-through. There have been no published comparisons of toxic gas yield data from closed chamber tests with full-scale test data. Limited comparison of data from the ISO 5660 Cone Calorimeter is not favorable, but no work had been conducted using the low oxygen cabinet. Preliminary comparison of data from the ISO/TS 19700 tube furnace is encouraging. There are as yet no consensus guidelines for performing such bench-sale/full-scale comparisons, but a document is under development in ISO TC92 SC3.

Transport and Decay of Combustion Products in Fires, *Marcelo M. Hirschler and F. Merrill Galloway Jr*, *GBH International*, *U.S.A.*

During transport from a fire to the locations where toxic fire gases might affect people, losses of the gases at surfaces are small for the majority of common combustion products. Acid gases, such as HCl, are a notable exception. Small- and large-scale experiments, with varying wall surfaces, have generated data on surface losses of HCl. Based on these data, a mathematical formulation was developed and integrated into a zone model of multi-compartment smoke transport. Hazard calculations indicate a significant degree of HCl loss to surfaces, with a resulting decrease in the toxic importance of HCl relative to CO. Other halogen acid gases are expected to behave similarly. Loss of HCN is smaller, but has not been as well investigated.

Physiological Effects of Combustion Products; *David A. Purser*, *Hartford Environmental Research*, *U.K.*

In addition to knowing the time- and space-dependent levels of the fire effluent, the estimation of the ASET requires a quantitative knowledge of the effects of the smoke and gases on the exposed people. There are some data regarding the effects of the components of fire effluent that can be used to estimate the effects on a person's ability to escape a fire environment. These include visible, and possibly irritant smoke, walking speed, decision regarding egress path, and incapacitation. A fractional effective dose (FED) model enables prediction of the onset of serious

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effect of CO and HCN. The acute effects of irritant gases are better described using a fractional effective concentration (FEC) model, since the effects from exposure are nearly instantaneous. Elevated temperatures and thermal radiation can lead to pain, incapacitation, and death. These data can be used in a hazard analysis to estimate which effect occurs first and whether combinations of effect might be important. Data on combined effects are scarce. A protocol is suggested in this paper for regulating toxic hazard.

Animal Inhalation Studies What Do They Tell Us? Jürgen Pauluhn, Bayer Healthcare AG, Germany

The exposure of laboratory animals to the effluent from materials or products burned under specified conditions provide an indication of the relative acute lethal toxic potency. The use of a hypothesis-based testing protocol greatly reduces the number of animals tested. Such a protocol enables technically sound interpretation of the results from both small- and large-scale fire tests. It removes the shortcomings of animal-free gas measurements, which cannot integrate the toxicological effects of the effluent components, cannot identify with certainty the presence of new components, and cannot provide information on any unexpected interactions of components. For assured assessment of fire safety, an animal inhalation procedure should be considered indispensable. The toxicological data should not be reduced to a single number, i.e. the LC_{50}, but need to be utilized in conjunction with information regarding the generation of the effluent and the potential exposure relative to other fire threats.

Regulations and Tests. Current Status and Future Developments; Jürgen Troitszch, Fire Protection Service, Germany

Only a few countries have toxicity requirements for fire effluents from materials and products in their building and fire codes. In the European Union (EU), reaction to fire testing of construction products does not include smoke toxicity. Poland has an animal-based toxicity requirement for interior finish and furnishings. Russia, China, and Japan have animal-based requirements for building products. The EU has gas measurement toxicity requirements for interior finish products' use in rail vehicles. The International Maritime Organization (IMO) has a gas measurement requirement for materials and components used in ships. There is no requirement for smoke toxicity in commercial aircraft, although the aircraft manufacturers use a test similar to that used by IMO for all components in the pressurized cabin.

How Can We Use This Information for Tenability Assessments? Richard G. Gann, National Institute of Standards and Technology, U.S.A.

Typical assessments of life safety in buildings do not explicitly consider toxic potency, the thermal and radiative environment, or smoke obscuration. This paper includes an outline of a rigorous approach that includes these factors, as well as a simplified approach. There are also implications for how one needs to characterize the contributions of individual combustibles to toxic fire hazard. Upon validation, the methodologies can be used to quantify the current levels of toxic fire hazard and to knowledgeably decrease the level.

2.2. *Smoke opacity, corrosivity, and heat release*

Smoke Opacity Test Methods; Stephen J. Grayson, Interscience Communications Ltd., U.K.

There are a number of test methods for the optical density of smoke from materials or cuttings from products. The fire models in these are quite diverse. Small-scale, closed chamber methods are widely used to regulate products. Small-scale, dynamic (flow-through) apparatus typically measures additional fire parameters. There are also large-scale tests that incorporate a smoke optical density measurement. The paper lists and describes most common methods used for fire smoke opacity assessment and was prepared as a reference document.

Smoke Production Properties and Measurement; Richard H. Whiteley, Consultant, U.K.

The properties of smoke aerosols generated in test methods depend very much on the material(s) being burned, the size of the specimen, and the completeness of the combustion. Both the smoke yield and the particle size distribution affect visual obscuration. Equations are presented for estimating smoke indices from closed and open test apparatus.

Smoke Scaling and Modeling Studies; Anne Steen-Hansen, Norwegian Fire Research Laboratory (SINTEF NBL), Norway

This paper presents two models for the prediction of optical smoke production in large- and intermediate-scale tests using cone calorimeter data. One predicts European smoke classification with a high degree of certainty for the materials tested. The other predicts time-dependent smoke production. The models may break down for fire retarded systems and for large-scale tests where the fire behavior depends on physical structures not represented in the small-scale cone calorimeter specimens, e.g. joints and seals. The low repeatability and reproducibility, which are worse than for heat release, affect the utility for borderline products.

Corrosion Test Methods; *Stephen J. Grayson*, *Interscience Communications*, *Ltd.*, *U.K.*

There are several similar test methods that heat a specimen in a tube furnace, collect the effluent, and measure the acid gases, and/or the acidity and the conductivity of the effluent. These results are thought to correlate with corrosivity and are used by the electric cable industries. There are four test methods that expose a metallic target to the combustion or degradation products. The measurements include metal loss and resistance changes on a circuit board. The paper lists and describes most common methods used for smoke corrosivity assessment and was prepared as a reference document.

Smoke Corrosivity of Combustion Products; *Archibald Tewarson*, *Paul Su*, *and Geary G. Yee*, *FM Global*, *U.S.A.*

Corrosion problems from fire effluent include damage to metal electrical contacts and sensitive surfaces in mechanical devices. Soot is an effective adsorbent for the vapors of corrosive compounds and enhances the corrosivity. Fuel-rich combustion conditions and elevated relative humidity enhance the smoke corrosivity. Corrosivity has been quantified using acidity/alkalinity and metal loss measurements and by measurement of leakage current. Improvements in the reliability and the repeatability of these measurements are underway. There is a need for generalized predictability of smoke emission rates, smoke deposition, and corrosive effects.

Heat Release Test Methods; *Vytenis Babrauskas*, *Fire Science and Technology Inc.*, *U.S.A.*, *and Stephen J. Grayson*, *Interscience Communications Ltd.*, *U.K.*

Heat release rates from fires of various sizes and natures are today generally measured using oxygen consumption calorimetry, although historic fire calorimeters typically measured heat output by thermal means. Oxygen consumption calorimetry replaced these due to its superior accuracy. Standards exist for several apparatus for measuring heat release rate, ranging from bench-scale to room-scale. Some large-hood calorimeters have capacities exceeding 10 MW. The paper gives a comprehensive review of the test methods used for heat release rate assessment and was prepared as a reference document.

Measuring and Predicting Burning Rate; *Marc Janssens*, *Southwest Research Institute*, *U.S.A.*, *and Patrick Van Hees*, *Lund University*, *Sweden*

Extensive published compilations of heat release rate measurements from burning products can be and are being used for fire hazard estimations, although those data may not necessarily apply to specific products under consideration. Prediction of the burning rate of a product in a fire on the basis of material properties measured in small-scale tests is, at present, limited. A reasonable capability exists for liquid and thermoplastic pools, interior finish, and upholstered furniture.

2.3. Hazards of combustion products: *Industrial sectors*

Hazard of Combustion Products in Maritime Fields; *Koichi Yoshida*, *National Maritime Research Institute*, *Japan*

Materials and products that are used in the accommodation areas of ships are regulated internationally to a uniform level of safety. Engineered fire safety design is permitted, to the extent that it provides the same functionality and level of safety as a series of prescriptive requirements. The prescriptive requirements include testing for ignition resistance, non-combustibility, surface flammability, smoke obscuration, and the generation of specific toxic gases.

The Future of Reaction to Fire Requirements for European Railways: *Limits for Products of Combustion*; *Gary J. Duggan*, *GJD Fire Ltd.*, *U.K.*

Within Europe, there are fire standards from the U.K., Germany, and France, which have derived from railway company standards. A CEN Technical Specification (CEN TS 45545) has been issued

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that contains prescriptive requirements for the emission of heat, visible smoke, and toxic fumes, mostly from the combustion of materials and products in standard bench-scale tests.

Assessment of Combustion Product Hazards for Aircraft; *Louise Speitel*, *Federal Aviation Administration*, *U.S.A.*

The stringent flammability requirements for aircraft cabin materials are based on performance in real-scale tests. The requirements are to be met for the life of the aircraft. There is no specific toxicity requirement. The goal of the FAA survivability model is to maximize escape time in post-crash fires. The model, which considers heat and toxic effects, is only used to demonstrate equivalency to products deemed as sufficiently safe. The input to the model comes from full-scale aircraft burn tests. The general model uses time-varying gas measurements to calculate fractional effective dose; a simplified model uses the gas measurements at 5 min. There are correlations between bench-scale and full-scale gas measurements. The model has been used to examine the effectiveness of alternative fire safety approaches.

Hazards of Combustion Products Industry Sector Report—Electric Cables, *Terence L. Journeaux*, *Prysmian Cables and Systems*, *U.K.*

The cable industry provides products with a wide range of fire performance to reflect varying customer needs. Tests for prescriptive requirements for cables include full-scale testing for flame propagation, intermediate-scale testing for visible smoke emission, and small-scale tests for corrosive and toxic gas emissions from cable materials. The recent activity has been toward combining these into a single test.

Hazards of Combustion Products—Construction; *Björn Sundström*, *SP Technical Research Institute of Sweden*

The European Construction Products Directive does not address smoke toxicity, and there is no activity in this direction. Limiting visible smoke from burning products and the fire growth rate is expected to also limit the amount of toxic effluent. Research is underway to link small-scale toxicity test performance to the same reference fire scenario that is used for flame spread and smoke generation testing. More research is needed on hazards from fire-generated smoke particles.

2.4. Conclusion

Quantifying the Combustion Product Hazard on the Basis of Test Results; *Vytenis Babrauskas*, *Fire Science and Technology Inc.*, *U.S.A.*

Regulation of toxic hazard on the basis of toxic potency is unsound and misleading, because it does not quantify the mass of toxic gases being released. From a manufacturer's point of view, a successful strategy to reduce fire hazard is to reduce the heat release rate rather than improve the toxic potency. Sufficient reduction in the heat release rate can prevent flashover, the point at which the mass of effluent increases sharply. Furthermore, the range of heat release values for a given product category is far larger than the range of toxic potency values, offering more opportunity for improvement.

3. DISCUSSION THEMES

3.1. General

There was extensive and lively discussion of the papers and the ideas they contained and stimulated. The following is a summary of those ideas, organized by topic. The reader should note that the summaries reflect what was expressed by the participants. A fuller portrayal of the state of the art in the various subject areas can be found in the presented papers.

One theme that pervaded the discussion, often beneath the surface, was the dual uses for measurements of toxic potency, smoke obscuration, corrosivity, and heat release. On the one hand, the measurement methods might be used in regulations to specify a reduced contribution to fire hazard from commercial products. On the other hand, the effluent data might be used in engineering design of buildings and in post-fire litigation.

In the following reporting, terms such as 'consensus,' 'agreement,' and 'disagreement' reflect the positions of people who spoke during the discussion sessions. No votes of the attendees were taken.

3.2. Toxicity

3.2.1. Nature of fire effluent. There was some sentiment that all fire effluent could be treated uniformly, i.e. the potency was always dominated by CO. The other voiced position was that effluent from different combustibles differed both in potency and in the gases that led to the observed toxic effects. The roughly fivefold range of reported toxic potencies favors the latter position.

Because of the relatively weak bonding of chlorine atoms to carbon atoms, HCl is generated early relative to the gasification of an equivalent mass of carbon. Thus, the apparent HCl yield will often be higher than that determined from the stoichiometry of the combustible(s). To get a true indication of the average HCl yield, it is necessary to track the degree to which the specimen is consumed and the residual composition (for specimens that are not totally consumed). Similar considerations apply to HBr generation as well.

In general, inhalable particles in the smoke affect acute toxic potency by transporting toxicants deep into the lungs. If the concentration of particles is high, their inhalation can lead to lung inflammation hours later, assuming that the person escape the immediate fire threat.

There is a limited knowledge of whether fire retardant additives in the form of nanometer-scale particles might present an additional toxic hazard. Any unusual toxicity would depend on the particles remaining at the nanometer scale. Soot is formed from the condensation of molecular species and is thus initially of nanometer dimension, although little of the soot mass remains as small particles at distances from the fire where people are likely to inhale it.

3.2.2. Transport of effluent. There was considerable discussion of the large losses of the strong acid gases (HCl, HBr, and HF) as the fire effluent travels away from the fire. There was uneven understanding of the two loss mechanisms: deposition of acid gases on walls, floors, and ceilings; and interaction with combustion-generated aerosols. Previous studies had indicated that surface losses are more important than removal by airborne aerosols. Thus, the apparent yield of acid gases depends on the nature of the walls and the distance from the fire. There was no recollection of a study examining the relationship between acid gas loss and the aerosol to acid gas ratio. Weak acids, such as HCN, are more persistent, i.e. they are not removed as effectively from the effluent stream by walls and aerosols.

This partitioning of the acid gases between the gaseous phase and the aerosol phase in the fire effluent led to discussion regarding the measurement of the acid gases in the fire effluent. It was suggested that Fourier transform infrared spectroscopy was unlikely to detect the acid gases that are absorbed on soot particles. Rather, the aerosol is trapped on the protective filter before it can enter the FTIR cell. The filter needs to be rinsed and the acid gases assayed. This leads to a time-integrated value.

Prior research had indicated that the adsorption of acid gases on particles is a mechanism that allows the acid gases to penetrate deeper into the lungs than gaseous acids, which are scrubbed by mucous membranes. Deeper penetration results in greater physiological harm. For fire hazard assessment, should a separate method be developed for acid gases contained in aerosols?

There was agreement that it was preferable to focus on measuring the yields of acid gases generated during burning and to use these values as input to computational fluid dynamics (CFD) models. The gas mixing within the CFD models, combined with a 'sticking coefficient', would provide for surface losses under different flows and surface configurations. This is not a feature of CFD models at present.

3.2.3. Scaling of effluent generation. There are complexities in relating the yields of toxicants generated in a real-scale fire test with the yields generated in a bench-scale device, using a specimen cut from the full-size product.

- It is desirable to use a single value for the yield of a toxicant from a combustible under specified combustion conditions.

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- In comparing the results from a bench-scale device with the results from a full-scale test, it is important to compare results from similar fire stages or from similar summation over fire stages. There is need for resolution of a protocol for comparing yields under 'transient' and 'steady state' fire test conditions.
- Full-scale fires are inherently transient and often span a number of different fire stages both temporally and spatially—for example, one part of an item may be burning well ventilated, whereas another part is underventilated. The current practice for full-scale fire tests is to use some kind of global equivalence ratio to characterize the fire stage and to look in the data for periods of time where there seems to be some kind of steady-state behavior.
- Not all reduced-scale tests generate a steady state that reflects the real-scale combustion.
- Accurate knowledge of the equivalence ratio is not assured in many large- and small-scale tests.

In comparing the measured yields of toxic gases among different tests or experiments, it is important to know the effective transmission of the gases through the often long sampling lines. Using a high flow through the sampling lines should keep losses low.

Data from a current round robin using the ISO smoke box with FTIR analysis of toxic gases (ISO/DIS 12489) are being analyzed. There are very large variations in the determined gas yields among the participating laboratories. These variations appear to be due (at least in part) to large differences in gas cells and pumping rates. At some point, for each physical fire model, it will be necessary to determine the sensitivity of the measurements to these parameters.

There was discussion of using the vitiated cone calorimeter as an additional test method that could provide toxic yield data, in particular for underventilated conditions.

- The widespread use of this apparatus for other fire measurements (e.g. heat release rate) makes this attractive. There are enough labs with these devices to conduct a round robin to determine reproducibility.
- There were two identified problems while using the apparatus: (1) the relatively high dilution of the fire effluent prior to the sampling location and (2) the potential, under vitiated conditions, for a flammable mixture to exist in the exhaust duct. The latter could be fixed using an afterburner.
- This apparatus captures the performance of a layered material early in a fire. If the upper layers break down, and the lower layers are exposed, some integration of effluent yields would be needed to compare with the product's performance in a real-scale fire.

3.2.4. Effects on people. There was general consensus that a two-gas equation (CO and HCN) for predicting fatal doses of narcotic gases was in good shape. Since an incapacitating dose is roughly half the lethal dose, a two-gas equation could be used for this effect as well. The dose is generally taken as the time integral of the inhaled concentration. For exposure to a constant concentration, this simplifies to the toxic dose being determined by the product of the concentration and the duration of inhalation. There was also general consensus on the levels of carboxyhemoglobin (COHb) and blood cyanide which were very dangerous to people. Depending on the activity level of the person, toxic effects could occur at lower exposures than they would for people at rest. There is also a good correlation between toxic exposures to CO for rats and people; similar exposure doses of CO lead to similar COHb levels, and the incapacitating doses are similar.

While it was generally agreed that CO played a role in nearly all fire deaths from smoke inhalation, there was some disagreement regarding the relative importance of HCN in fire deaths.

HCN is produced by the burning of some common materials found in building contents and furnishings. However, forensic evidence for cyanide intoxication is not very reliable, due to delays in acquiring blood samples (and blood cyanide increases after death) and uncontrolled storage of the acquired samples. As a result, there are few usable data on blood HCN levels in fire victims.

Experiments with laboratory rats have shown significant effects of additional gases, such as halogen acids, nitrogen oxides, and sulfur dioxide. There has been no extrapolation of the effect of levels of these additional gases to people.

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There is fair knowledge of the effects of reduced oxygen on people. However, the data were determined from high-altitude simulation chambers, not from displacement of oxygen by other gases as in a fire. Thus, our modeling of hypoxia may not be correct.

There was disagreement regarding whether sensory incapacitation from acid gas exposure was better represented by an immediate incapacitation (FEC) model or a dose-based (FED) one. The time frame for these dose effects is far shorter than for the dose effects of, e.g., the narcotic gases. This issue is being discussed in ISO TC92 SC3, with implications for revision of ISO 13571.

There was no clear answer whether nanoparticle fire retardants present a new form of toxic risk, based on their small size and potential surface activity. It was not known whether these particles are released into the effluent when an item is burned. The nanoclays are designed to form a blocking layer within the burning item, and thus are expected to remain within the unburned residue. For other nanoscale retardants, there is an analogy with soot formation. Soot begins as molecular fragments that increase in size, eventually becoming particles of micrometer or larger size. Nanoretardant particles of similar surface character would be expected to grow as well. Nanoparticles with particularly inert surface activity would be expected to remain dispersed and at the nanoscale. The surface characteristics that might effect significant toxicity have not yet been characterized.

3.2.5. Bench-scale toxicity measurement/regulation. There was consensus that data from bench-scale toxicity tests should *not* be used as stand-alone criteria for product acceptance or regulation. Nonetheless, the current toxicity regulations do just this, relying on limiting gas concentrations generated in the test or on indexes calculated from these concentrations.

There are differences in the design fires that should be incorporated in building design for assessing tenability effects on people. This affects the conditions replicated in real- and bench-scale fire tests. In North America, most fire deaths have been the result of either smoldering fires or post-flashover fires. Conversely, in the U.K., deaths from fires are most often small fires that become vitiated, do not go to flashover, and do not spread far from the room of origin. (These were presented anecdotally, but there are national fire statistics that support these statements.) This variation is likely the result of different means of construction, different furnishing habits, and somewhat different materials employed in the two regions. This variation suggests that only with caution should one generalize the findings from either of these two regions to other regions of the world. The different fire stages described in ISO 19706 may have varying levels of relevance depending on which country or jurisdiction is being considered.

There was discussion of the effectiveness of different approaches in reducing deaths from toxic products from fires. There was agreement that consideration of the role of construction products, but not contents and furnishings did not make much sense, since the contents were most frequently responsible for the initial generation of a toxic environment. Stand-alone toxic yield tests have the potential to be abused by authorities having jurisdiction. The concept was proposed that, because toxic yields are dependent on the fire conditions, making them difficult to predict for any individual case, better success could be found in reducing fire growth and spread. This approach was pursued later in the Conference.

3.3. Visible smoke

In quantifying smoke production, the two important parameters are yield (in g/g) and extinction area or optical density. The first indicates the mass produced, and the latter allows quantification of the degree to which visibility is diminished. A relationship between these two properties has been established for flaming combustion at small scale. However, the use of this relationship leads to underprediction of the smoke yield in room-scale tests. Further work is needed to determine which of these two smoke parameters is more appropriate for characterizing a burning product's contribution to fire hazard.

Two important factors affecting correlations of smoke yields between bench, intermediate, and full scale appear to be whether the sample fully burns or not and the fact that at larger scales there is more simultaneous burning at different fire stages. Such scaling correlations to date are not

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convincing. Fire retarded, i.e. less efficient burning, products show an increase in smoke yield in both small and intermediate testings. The possibility was raised that the smoke from room-scale tests might be predicted using cone calorimeter data for both overventilated and underventilated burning.

As smoke ages, it undergoes several processes that will likely improve visibility, including agglomeration, sedimentation, and wall deposition. It was unlikely that a single cone calorimeter test would be able to predict the larger scales; multiple tests under different conditions might improve the predictions. It was also noted that the nature of the object you want to see, such as whether it is light emitting or reflecting, as well as whether the smoke is scattering (white) or absorbing (black) will be factors affecting visibility.

3.4. Heat release

Most correlations between the heat release of furnishings, wall coverings, etc. and bench-scale specimens have been for products of high or ordinary heat release rate. The correlations for desirable, low-heat release products have not been successful. This is because the flaming of the full product is often 'dancing' and because of the large uncertainty in the heat release measurements at low oxygen consumption. It was offered, with no consensus, that it might be sufficient to know that a product is of very low heat release rate without having a quantitative value.

Knowledge of the uncertainty in heat release measurements is of critical importance. It is not known how uncertainty in a heat release measurement would affect the prediction of performance in a real fire. Under current practice, the large uncertainty for low-heat-release-rate materials is acceptable. This criterion may be application-specific—the example of spacecraft was mentioned, where low flammability with low uncertainty is desirable.

There was extensive discussion regarding the role of the microscale calorimeter. The device is essentially an improved thermal analysis device and has a role to play in materials' research and development. There was general agreement that the apparatus is best used as a tool for screening material formulations for potentially low or very low heat release rate. Such materials have proven troublesome in the cone calorimeter, where the uncertainty of the measurement can be as high as 100%. However, it does not characterize the heat transfer phenomena and layering effects of larger test specimens, which play a significant role in real-scale fires. The device would not replace larger bench-scale methods, such as the cone calorimeter, in determining heat release rate.

3.5. Status of product requirements

3.5.1. Ships. There appeared to be anomalies in the safety to life at sea (SOLAS) requirements. The SOLAS flammability requirements for interior finish materials are more stringent than those for aircraft. This may be argued as being due to the large size of cruise ships and the large number of people onboard; however, such a risk analysis has not been presented. The requirements for furniture and mattresses only address resistance to smoldering ignition; there are no requirements to mitigate self-heating.

The trend toward ships with lighter superstructures (e.g. high-speed craft) may lead to alternative approaches to fire protection.

The toxicity requirement is defined using a stand-alone gas concentration test. This approach was generally felt to be improper (See Section 3.2.5.).

3.5.2. Trains. There appear to be no systematic data on deaths in railway vehicle fires in general.

There was pointed discussion regarding the very strict limitations on halogen acid emissions that are used in the selection of materials for European rail cars. On the one hand, perhaps the restriction on irritants is reasonable because they may interfere with evacuation. On the other hand, these restrictions are more rigorous than those for most other applications. These pass/fail decisions are based on a stand-alone test method, an approach which was not well regarded by those at this conference.

It was noted that the U.S. does not use smoke toxicity information in its materials selection for rail vehicles, and that there are not extensive reports of people dying in rail car fires. However, rail vehicle manufacturers impose their own standards on their suppliers.

3.5.3. Commercial aircraft. There is evidence that flammability regulation of materials used in aircraft had a real impact on the survivability in aircraft fires. The time window for escape is much smaller for aircraft than in general. Only the first 3 to 5 min are important, and adding even an extra minute for evacuation is significant.

3.5.4. Electrical cables. The cable exposure in the EU flammability (ladder) test includes forced ventilation. This is to keep the effluent from extinguishing the burning. The IEC test has natural ventilation, which leads to a reduced thermal attack on the cables. There was no indication of the effect of ventilation conditions on the generation of smoke and toxic gases.

3.5.5. Construction products. Prescriptive classification of building products for toxic potency is uncommon. The precision of the measurement of toxic products is increasing. However, as noted in Section 3.2.4, precise quantification of the effects of toxic gases, other than CO and HCN, is a research issue.

3.6. How best to advance fire safety

3.6.1. Reduction of product contribution. There was spirited discussion of whether one should attempt to improve the fire safety of products only by improvement in heat release rate, and specifically not by toxic potency. This is because the reported range of heat release values is much larger than the ranges of LC_{50} or IC_{50} values. Large improvements in maximum heat release rate have been realized for a whole class of prime combustibles in residential fires: In the U.S., the heat release rate of a mattress and foundation is limited to 200 kW, an order of magnitude lower than the prior typical rate of 2 MW.

3.6.2. Estimation of toxic hazard. Even with such product improvements, a number of future fires are likely to be large enough to pose a threat to life and property loss. Furthermore, while selection of products based on experience with 'bad actors' and stand-alone testing of products may be effective for today's products and materials, a hazard analysis may be necessary for new products and materials. For instance, the new U.S. mattress standard is commonly being met by surrounding nearly all the combustible content with a barrier material. While this reduces the flaming considerably, the possibility now exists for vitiated burning within the barrier volume.

Thus, engineering tools to estimate fire hazard are essential. The inclusion of toxic hazard, as a component of overall fire hazard, is merited since statistics indicate that most fire victims die from smoke and toxic gas inhalation. Furthermore, regulators (specifically in the EU in regard to transportation) are moving toward regulating products based on toxic hazard in fires, and if the technical community does not provide sound guidance, there is a risk of unproductive regulatory decisions. The guidance must be both accurate and easy to use.

As noted in the Conference papers, there are a number of factors affecting the contribution of an item to toxic hazard in a fire. In general, toxic hazard is more complex than a toxic potency value (LC_{50} or, more appropriately, IC_{50}). It is broadly determined by the rate of production of toxicants and the exposure of people to those toxicants. There was concurrence that IC_{50} values alone do not reflect toxic hazard: a short exposure to a high concentration may be survivable. It was also suggested that, from a regulatory perspective, it might be more effective, though conservative, to assume that escape is difficult or impossible, as is done for fires on board a ship or aircraft.

The discussion led to various, often contradictory statements regarding which component of fire effluent was the first to create an untenable exposure: heat, CO, smoke obscuration, irritant gases. It was suggested that useful information could be gained through simulation of a multi-room fire. By varying the contents, their rates of heat release, etc., one could show both the magnitudes of the effects of these parameters on the components of effluent hazard and determine whether there was a consistent component that was the first to limit tenability. However, care is needed in selecting the fire scenarios and the assumptions used in the simulations.

3.6.3. Regulation of products. There was extensive discussion of approaches to regulatory characterization of products for their role in toxic hazard.

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While it was suggested that assigning a single number to a product would promote ease of use, this introduced significant simplifications that would require research and analysis, e.g.:

- Is determining the potential to lead to flashover a sufficient test result to use for regulation?
- Can one subject products to a single fire scenario with a pass/fail criterion, realizing that the toxic products change greatly, e.g. as the fire becomes vitiated?
- Can one sum IC_{50} values over a test of a product, in order to get a single number for use in regulation?
- Will reducing the assessment of a product to a single number produce incorrect assessment of toxic hazard, given different fire stages, etc?
- Since, in product testing and approval, people's eventual exposure time to the effluent is unknown, how does one arrive at a criterion for suitability of use of the product?

More complex approaches were also considered, such as combining test data with a computer simulation. The output from this would be complex, and the guidance to regulators needs to be simple/succinct/direct/accurate.

It was noted that successful regulation of products to improve fire safety would necessarily lead to changes in some products, removal of some products from the market, and opportunities for new products that might not have been commercially feasible beforehand. Agreeing on a regulatory scheme would be difficult, with manufacturers of current products potentially urging provisions that do not require major product changes and safety advocates supporting changes as long as they improve survivability and safety.

A specific topic of discussion was the potential use of the ISO 9705 room testing of products to generate data for estimating toxic hazard. There was disagreement regarding the suitability of the fixed burner as an ignition source and whether the configuration was representative of the end use—specifically for wall linings. It was noted that in Europe, the product being tested covers the walls and the ceiling, whereas in the U.S., the product covers the walls only.

A question was posed regarding the ability to estimate the potential for incapacitation from a full-scale fire. Small-scale apparatus are currently being evaluated for their accuracy in generation of toxicants relative to burning of the same products at room scale. The possible quality of those relationships is unclear at this time. There are equations that relate exposure to the various components of fire effluent to incapacitation. These equations have been reached by consensus of experts in fire science and fire toxicology.

A common theme in this discussion was the need to establish a small number of reference scenarios for which test data could be developed and fire simulations conducted. These could provide better guidance on potential paths to product characterization for their role in toxic hazard assessment.

3.6.4. Other approaches. Improvements in life safety can come from other approaches than flammability control, such as building design and egress management. These can have large effects on the exposure to the fire effluent.

There are apparently cultural factors that affect the outcome of people management and education. In the U.S., extensive resources have been devoted to this, but the decades-long reduction in fire deaths is generally attributed to the advent of smoke detectors and increased flammability standards, rather than behavioral changes in emergencies. Of course, the public needed to be educated in the value of buying and installing the smoke detectors. In the U.K., community education and the installation of smoke detectors have led to a 50 % reduction in fire deaths over the past 30 years. The common factor is the proliferation of smoke detectors, but the role and effectiveness of fire safety education appears to differ.

3.6.5. Priority research areas. At the end of the meeting, four experts were each asked to identify one area they would like to emphasize for improving fire safety. They were:

- Provide a hazard number or class system for products that has some meaning. Otherwise, there is the potential for a system of high uncertainty and with no assured benefit to fire safety.

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- Develop a standard for low-flammability upholstered furniture along the line of the U.S. standard for low-flammability mattresses. Note, however, that there might be unintended consequences, such as an increased use of environmentally objectionable fire retardants.
- Focus IMO regulatory testing on a heat release rate test protocol and base revised requirements on a sound rationale and documented basis.
- Increase efforts in fire safety education and community support, while making fire tests performance-based and better corresponding to full-scale performance.

REFERENCES

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