ON THE USE OF BENCH-SCALE SMOKE TOXICITY DATA IN FIRE HAZARD AND RISK ASSESSMENT

Richard G. Gann
Senior Research Scientist
Fire Research Division
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD USA

INTRODUCTION

Fire safety engineering of facilities increasingly includes some degree of assessment of the tenability by occupants of a building in the event of a fire. These assessments include estimates of the time available for people to escape a burning facility or find safe refuge within. Today's fire safety professionals use diverse and *ad hoc* approaches to make these assessments because:

- There is no standard protocol for estimating the time available for escape.
- There is no agreement on which toxicological effect(s) to base the estimation of time available for escape.
- There is no widely accepted methodology of known accuracy for generating the smoke toxic potency data needed to implement the estimation.

The first shortfall is being addressed by professional and standards organizations, including ISO and ASTM. A truly quantitative methodology is critical. As noted in a recent analysis by Hall[1], some 310,000 to 670,000 people in the United States alone are exposed to smoke from reported home fires. He further finds[2] that:

- "Roughly half of the deaths and roughly two-thirds of the injuries could be prevented were the times to incapacitating exposures lengthened sufficiently to result in a more favorable outcome.
- This also requires the addition of smoke alarms for most sleeping victims and an assumption of success and survival close to the fire by the victims attempting rescue or fire control.
- Only providing extra time would probably help only the victims who were attempting escape, and they represent only one-fourth of fatally and non-fatally injured victims."

The second shortfall has recently been addressed by ISO TC92 SC3 on Fire Threat to People and the Environment. ISO Technical Specification 13571[3] presents

- A consensus view that incapacitation, the inability to effect one's own escape, is the effect of fire effluent on people that is a proper basis for safety estimates.
- Consensus equations for including the incapacitating effects of fire gases, heat, and smoke obscuration in fire risk and hazard analyses.

This paper addresses the third shortfall: obtaining accurate, quantitative data on the incapacitating potency of fire effluent.[#] This information can be in one of two forms. It could be from measurement of the exposure that incapacitates laboratory animals, followed by extrapolation from that species to people. It could also be from measurements of the yields of the harmful combustion products. These numbers would then be used in equations such as those in ISO/TS 13571.

SOURCES OF TOXIC POTENCY DATA

These data can be derived from real-scale burning of commercial furnishing and building products. However, given the number of such products in use in residences, public assembly facilities, transportation vehicles, etc., the cost of such testing would be inordinate, even if the world's collective test laboratories had the capacity to perform the work.

An alternative approach is to derive the needed data from the burning in a bench-scale apparatus of small specimens cut from commercial products. Numerous devices have been developed for this purpose, falling into four general designs:

- Tube furnaces, such as DIN 53436;
- Cone Calorimeter (e.g., ISO 5660-1);
- Radiant panel apparatus (ASTM E1678/NFPA 269); and
- Closed box combustors, such as ISO 5659-2.

Knowing which device to use, *i.e.*, which devices gives valid representations of reality, is essential. Underestimating the toxic potency could result in a hazard analysis not providing the intended degree of safety. Overestimation could inappropriately bias the marketing of construction and furnishing materials, constrain and distort building design options, and drive up construction and occupancy costs.

Determining the accuracy of these devices requires three components: fire effluent data from some set of real-scale fires, data from the bench-scale device for the same test materials, and a basis for comparison of the results. The data can be obtained using analytical instrumentation or test animals as the measuring devices. In all cases, knowing the uncertainty in the measurements is pivotal in assessing the quality of the bench-scale device. The three components are discussed further in the following sections.

Real-scale Data for the Different Stages of Fires

The international community has reached agreement on the characteristics of the stages of fire. These are delineated in Table 1.[4]

While numerous series of room- and larger-scale fire tests have been conducted, few of these have attempted to segregate the fire stages. One series of room-scale tests had been conducted from which both gas yields and animal (rat) lethality were estimated.[5] The data were specific to the post-flashover stage of the test fires. The products examined were Douglas fir, a rigid polyurethane foam, and an unplasticized polyvinylchloride. The yields of toxic gases and the LC_{50} values[*] were compared with data from the NBS cup furnace, the Cone Calorimeter, and the radiant apparatus that became ASTM E1678/NFPA 269. The last of these gave the best agreement to the room test data.

[#] "Fire effluent" includes all the products of combustion: gases, aerosols, and heat.

[*] The LC_{50} is defined as the concentration of a toxic gas or of fire effluent statistically calculated from concentration-response data to result in the deaths of 50 % of the test animals within a specified exposure and post-exposure time. The IC_{50} is the comparable value for incapacitating the animals.

Table 1. Characteristics of Fire Stages[4]

Fire Type	Heat Flux to Fuel Surface kW/m^2	Max. Temperature, °C		% Oxygen (volume)		Fuel/Air Equivalence Ratio (Plume)	$\frac{[CO]}{[CO_2]}$ (v/v)	% Efficiency $\frac{100 \text{ x } [CO_2]}{[CO_2]+[CO]}$
		Fuel Surface	Upper Layer	Entrained	Exhausted			
1. NON-FLAMING								
a. Self-sustaining (smoldering)	n.a.	450-800	25-85	20	. 20		0.1-1	50-90
b. Oxidative pyrolysis from externally applied radiation		300-600 [1]	[2]	20	20	1	[3]	[3]
c. Anaerobic pyrolysis from externally applied radiation		100-500	[2]	0	0	1	[3]	[3]
2. WELL VENTILATED FLAMING[4]	0-60	350-650	50-500	≈20	.20	≈0.1	0.05 [5]	95
3. UNDERVENTILATED FLAMING[6]								
a. Small, localized fire, generally in a poorly ventilated compartment	0-30	300-600 [1]	50-500	15-20	5-10	0.1-0.5	0.2-0.4	70-80
b. Post-flashover fire	50-150[1]	350-650 [7]	600	15	5	[8]	0.1-0.4	70-90

NOTE 1 The upper limit should be lower than for well ventilated flaming combustion of a given combustible.

NOTE 2 The temperature in the upper layer of the fire room is most likely determined by the source of the externally applied radiation and room geometry.

NOTE 3 There are few data, but for pyrolysis this ratio is expected to vary widely depending on the material chemistry and the local ventilation and thermal conditions.

NOTE 4 The fire's oxygen consumption is small compared to that in the room or the inflow, the flame tip is below the hot gas upper layer or the upper layer is not yet significantly vitiated, the flames are not truncated by contact with another object, and the burning rate is controlled by the availability of fuel.

NOTE 5 The ratio may be up to an order of magnitude higher for materials that are fire-resistant.

NOTE 6 The fire's oxygen demand is limited by the ventilation opening(s); the flames extend into the upper layer.

NOTE 7 Assumed to be similar to well-ventilated flaming.

NOTE 8 The plume equivalence ratio has not been measured; the use of a global equivalence ratio is inappropriate.

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Another such set (pre- and post-flashover yield data for room fires of sofa mockups, bookcases, and an electric power cable) has been provided by the NIST/Fire Protection Research Foundation project *International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS)*.[6] The products were selected for complexity of form and composition, differences in burning behavior, and expected variety in the relative importance of the different toxic combustion products. For both pre-flashover and post-flashover fire stages, the report contains yields of chemical species of importance to hazard analysis: CO, CO_2, HCN, HCl, carbonaceous soot, with upper limits for NO, formaldehyde and acrolein. These values establish a database for assessing the accuracy of bench-scale devices. Additional samples of the test materials have been maintained for a future study to establish a validity assessment protocol for the four test method groups listed earlier.

Data from Bench-scale Devices

Since the 1960s, numerous bench-scale devices have been used to develop information on the gases generated and their effects on laboratory animals.[7] The combustion conditions in some of these can be related to specific fire stages; in others there is either ambiguity or no relationship. A recent paper compiles a large amount of animal (rat) exposure data from over 200 publications.[8] The test specimens included over 30 types of materials and products. The authors grouped the data from those devices whose combustion conditions could be related to oxidative pyrolysis, well ventilated flaming, or underventilated flaming (stages 1b, 2, and 3, respectively, in Table 1). The results are summarized in Table 2. Mean values are shown for those who need a generic value for a hazard analysis in which the actual combustibles are unknown. However, the broad confidence intervals indicate that materials and products can manifest a wide range of lethal toxic potency values and that these generic values must be used with caution.

Similar tabulation and analysis of gas yields from the various devices are needed.

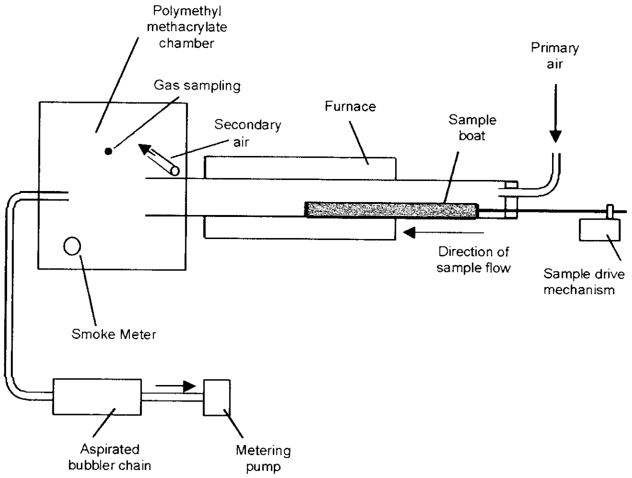
The ratio IC_{50}/LC_{50}, *for those specimens where both were determined*, is 0.50 ± 0.21.[8] [Note that this is not the same as taking IC_{50}/LC_{50} ratio from Table 2, since the data set includes many materials for which only one of the two values was determined.] In this set of test specimens, the combinations (and ratios) of gases leading to the effects vary considerably. Thus, this factor of two is likely to be general in nature.

Table 2. Estimated Values for Lethality and Incapacitation[8]

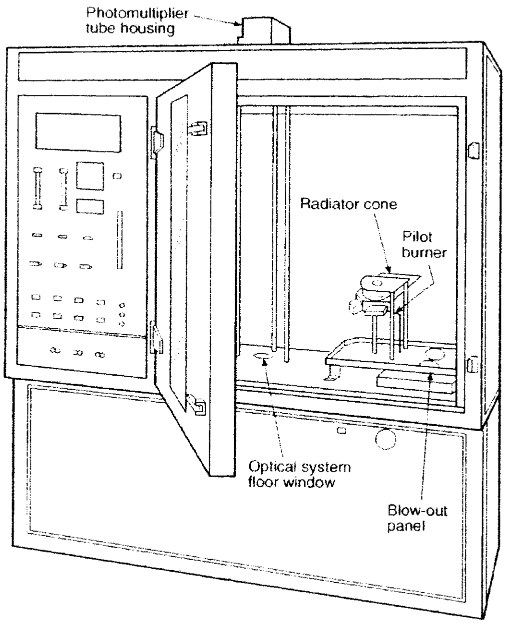
Property (g/m^3)	Material	Well-ventilated Combustion	Ventilation-limited Combustion	Oxidative Pyrolysis
LC_{50}	Estimated mean	30.1	24.4	27.8
	95 % Confidence Interval	(5.1,58.0)	(15.8,40.3)	(1.6,78.4)
IC_{50}	Estimated mean	11.2	---	11.5
	95 % Confidence Interval	(1.4,24.0)	---	(1.1,25.0)

Careful analysis of the operating conditions in the bench-scale devices themselves is important since the local combustion conditions and test specimen preparation differ widely. Thus, there could be diverse and perhaps conflicting effluent data available for a given commercial product. Such an assessment is underway in ISO TC92 SC3. ISO/TS 16312-1 presents a set of criteria for the process.[9] Currently under development by the Subcommittee is a Technical Report (to become ISO/TR 16312-2) that applies those criteria to apparatus currently used to obtain information on fire effluent. The following are examples of *this author's* assessment of the four types of combustors listed above.

Tube Furnaces: A schematic of one such device is shown on the right. These devices typically are operated at one or more fixed temperatures, although ramped temperatures have been used. Ignition can be spontaneous or initiated. In some apparatus, the test specimen size is limited to a 1 g magnitude, in others much larger specimens are possible. The test specimen must conform to the tubular shape. For homogenous materials, this is not a problem. However, most finished products must be diced to be accommodated, so the combustion may not reflect the intact product, especially for layered or inhomogeneous products. The air flow into the tube is set independently, so an initial fuel/air equivalence ratio can be selected to reflect a chosen degree of ventilation, although this will vary if the combustion rate or specimen shape changes during the test. For specimens undergoing flaming, the flames will impact the top surface of the tube, promoting the formation of (more toxic) products of incomplete combustion. The specimen mass loss can be determined, effluent concentrations can be monitored, and small laboratory animals can be exposed, thus enabling calculation of combustion product yields and animal lethality and incapacitation. Conceptually, the flow and thermal conditions make such devices capable of replicating the pyrolysis and flaming stages of fire. However, the local flow and combustion conditions are complex and the application to various fire stages needs to be determined for each such device.



Closed Box Combustors: These devices also vary in size and design; one version is shown in the accompanying figure. In these devices, the test specimen is exposed to a small flame, a radiant element, or a furnace. Ignition of the test specimen can be spontaneous or initiated. The test specimen is generally small in mass, but could be representative of a larger, inhomogeneous product. The sample mass loss and product gases can be sampled, enabling determination of combustion product yields. A smoke meter enables determination of smoke optical density (and by inference smoke mass). During a test, the environment in the chamber is vitiated for all but the smallest or least flammable specimens, making assignment of a particular fire stage difficult and promoting the formation of (more toxic) products of incomplete combustion. Vitiation can also lead to quenching of flames during the test. Moreover, over the course of the test all of the combustion product yields will vary significantly as vitiation increases. It is not feasible to extract a sufficient volume of the atmosphere to perform animal exposure tests. However, in at least one design, an animal exposure cage has been inserted into the test chamber to obtain incapacitation data. Heat effects must then be separated from toxicity and oxygen depletion effects. The apparatus is



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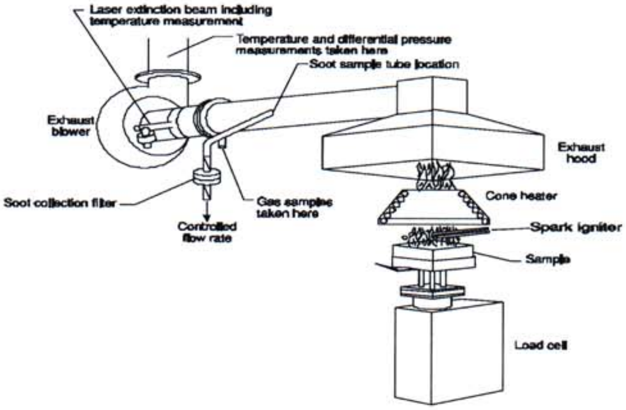
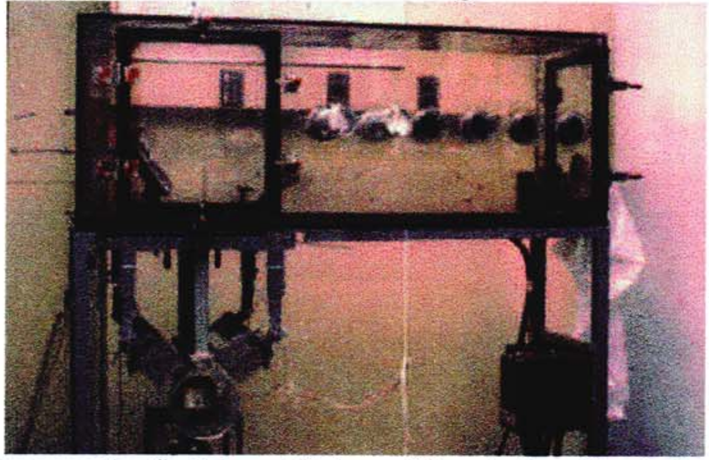
intended to replicate conditions where flaming combustion poses a serious hazard. However, the change of combustion conditions during a test makes it unclear whether the data are applicable to any specific fire stage.



Cone Calorimeter: This apparatus is intended for measuring the rate of heat release (RHR) of test specimens, but has been suggested for generating toxic product yields. Here, a representative specimen (up to 100 mm square and 50 mm deep) of a finished product is exposed to a uniform radiant source, with irradiances ranging from those characteristic of small flames or low-level pyrolysis up to post-flashover conditions. In the standard configuration, highly overventilated combustion results from a forced air draw. In some devices, the test specimen is contained in a flow-through box, enabling independent control of the combustion environment and the air flow. The specimen is weighed continuously and product gas concentrations are measured in the effluent stream, enabling calculation of combustion product yields. Because of the high air flow, the concentrations of products are low. Thus diversion of some of the exhaust stream to an animal housing is unlikely to produce incapacitating exposures. A laser in the exhaust tube enables determination of the smoke optical density. Even at high irradiances typical of post-flashover fires, the standard device underestimates the concentrations of combustion products. The applicability for well ventilated fires and the accuracy of the controlled ventilation device for all fire stages remains to be assessed.



Radiant Panel Apparatus: Here also, a representative cutting of a finished product is exposed to a uniformly radiant source, with irradiances ranging from those characteristic of small flames or low-level pyrolysis up to post-flashover conditions. A spark igniter initiates flaming. The hot combustion products rise through a chimney into a large plastic box, while the combustion draws air to itself from the box through two other conduits. The specimen is weighed continuously and the box environment is sampled continuously (and returned to the chamber), enabling calculation of combustion product yields. Small animals (rats) are exposed (head only) throughout the test, enabling determination of lethality and incapacitation. The results correlated reasonably well with real-scale post-flashover results, after a correction for high post-flashover CO production. The physics are appropriate for good replication of pre-flashover fires, but this remains to be assessed.

In summary, researchers have devised a number of diverse apparatus for obtaining information regarding the toxic potency of combustion effluent. Given the major differences in the character of test specimens and of the combustion conditions, it is unlikely that these devices will generate similar effluent. This emphasizes the need for an objective set of criteria for comparison with real-scale test

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results. To the extent that such a comparison is based on data for a diverse range of test specimens, there will be confidence in the validity of the bench-scale device.

Methodology for Comparing the Results and Estimating the Accuracy of the Bench-scale Data

Such a comparison could well involve measurement of the effects of the effluent on laboratory animals and the extrapolation of these effects to people. Animals integrate the effect of all the effluent components, and there are toxicological conventions for relating the results to people. One recent approach links the typical rat lethality data to the incapacitation of smoke susceptible people in the short exposures expected in most fires.[10] However, animal testing is increasingly difficult to obtain. Protocols based on animal responses are probably constrained to little more than the existing data. This set is not sufficient for robust validation of bench-scale apparatus.

Comparisons may also be based on the comparability of the yields of the individual toxicants or their projected combined effects. This is a more appealing approach societally, but has the risk of missing the contribution of one or more unidentified or unmeasured toxicants.

There are also multiple approaches to performing the comparison between bench-scale and real-scale effluent, such as:

- Calculating the degree of agreement and determining whether it is within the combined uncertainties of the two data sets.
- Determining a degree of agreement that is sufficient for the risk or hazard assessment at hand and accept any value that is smaller.
- Calculating and publishing a degree of agreement for a given apparatus, allowing future users to make their own determination of sufficiency.

The following, adapted from references 5 and 9, comprises a set of increasingly challenging criteria for comparing the ability of bench-scale apparatus to replicate the effluent hazard from real-scale fire tests for the *same* test material. [Note that materials or products that are from the same generic polymer family, e.g., polystyrenes, may produce smoke that is quite different in composition and toxic potency.] In performing such a comparison, there are multiple considerations, such as the uncertainty in both sets of test data, the extent to which the real-scale test replicates the real-world hazard of concern, and the diversity of the materials and products that are included in the data set.

Comparison of IC_{50} Values: These can be obtained by exposure of laboratory animals or by calculation from gas concentrations.

- When laboratory animals are exposed to the effluent, the comparison is between the IC_{50} value determined from a test specimen burning under conditions simulating a selected fire stage and the IC_{50} value from the same stage of combustion of the commercial product at real scale.
- When no animals are exposed to the effluent, the comparison is between the IC_{50} value estimated from the species yields from a test specimen burning under conditions simulating a selected fire stage and the IC_{50} value estimated for the species yields from the same stage of combustion of the commercial product at real scale.
- If only LC_{50} values are available, one can assume it is double the IC_{50} value (see above).

It should be noted that it is possible to obtain the same IC_{50} value for very different effluent compositions. Thus, numerical similarity of these terms is not a sufficient basis for assessing the accuracy of an apparatus.

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Comparison of the Primary Toxic Gases: For this comparison, yields of the potentially toxic gases are needed. One uses an equation that combines the effects of the gases into an effect on laboratory animals[11] or an estimated effect on people.[3] In each case, there will be a set of gases that account for the lethality or incapacitation to within, e.g., ± 20 %. Ideally, the gases in these sets should be identical, or at least any significant differences should be rigorously explainable.

Comparison of Yields: The primary comparison is between the yield data for combustion products from a test specimen burning under conditions simulating a selected fire stage and yield data from the same stage of burning of the commercial product at real scale. The accuracy of yield data from a physical fire model is determined by the degree of numerical agreement with yield data from real-scale fire tests. The determination takes into account the repeatability and reproducibility of the data from both the reference tests and the physical fire model. Typical yield data include the following:

- CO_2: This is a marker for the mass burned. The yields of the gases contributing to the toxicity are equal if there is overlap between the numerical ranges defined by their respective measurement uncertainties. The measurement uncertainty is generally less than 20 % of the yield value.
- CO: The yields are considered to be equivalent (a) if the bench-scale value is within ± 30 % of the real-scale value or (b) if there is overlap between the numerical ranges defined by their respective measurement uncertainties, whichever is larger. A compilation of post-flashover CO yields[12] shows that the yield of CO from post-flashover room fire tests of a variety of combustibles is 0.24 ± 0.09. Since the high CO yields result from vitiation (and thus from truncation of the fuel oxidation process) in the upper layer of the burn room, a physical fire model may be unable to replicate this result.
- HCl, HBr, HF, and HCN: The yields are considered to be equivalent (a) if the bench-scale value is within ± 50 % of the real-scale value or (b) if there is overlap between the numerical ranges defined by their respective measurement uncertainties. There may be significant losses of these gases during sampling, and these losses may differ between the two apparatus. These losses need to be considered in comparing the results.
- Partially oxidized organic compounds (e.g., acrolein, formaldehyde): The yields from the physical fire model and the real-scale fire tests are considered to be equivalent (a) if the bench-scale value is within a factor of two of the real-scale value or (b) if there is overlap between the numerical ranges defined by their respective measurement uncertainties.
- Trace toxicants: If the yield of any of the above gases contributes less than 2 % to the total toxic potency (using the equations from ISO 13344 or TS 13571) then the yield from the physical fire model is considered to be equivalent if it is within a factor of 5 of the real-scale test value.
- If the yields values from the validation tests are not equivalent, the degree of agreement is described by the ratio of the value from the physical fire model divided by the value from the real-scale fire test.
- An additional criterion is that the relative importance of the individual terms in equations (2) and (4) of ISO/TS 13571 must not change in importance due to the different values from the real-scale and bench-scale determinations.

Alternatively, one could deem the bench-scale device to be of sufficient validity if the agreement is within a pre-selected value.

Comparison of Animal Effects: This clearly applies only to cases where laboratory animals have been exposed to the fire-generated atmospheres in both the bench-scale and real-scale tests. Differences might include deaths of the animals at different times (within exposure vs. days later), different symptoms observed during the test or revealed during an autopsy, etc.

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CONCLUSION

A need exists for accurate determination of the incapacitating potency of effluent from burning commercial products for use in fire risk and hazard analysis. Most of these data will be derived from gas yield measurements in bench-scale apparatus. The process for obtaining, evaluating the relevance of, and using the data in fire risk and hazard analysis is being standardized. A multi-tier approach to determining the accuracy of the effluent data is presented. It is likely that some of the currently used bench-scale devices are not generating technically accurate data and will need to be replaced if the hazard and risk analyses are to be defensible.

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