

ASSESSING THE ACCURACY OF A PHYSICAL FIRE MODEL FOR OBTAINING SMOKE TOXIC POTENCY DATA

Richard G. Gann, Jason D. Averill, Nathan D. Marsh, and Marc R. Nyden
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8664 USA

INTRODUCTION

A principal component of the engineering of a building is providing for the safety of occupants and responders in the event of a fire. This includes estimation of the time available for people to escape or to find safe refuge within. An accurate, quantitative methodology for this estimation is critical. As noted in a recent analysis by Hall¹, some 310 000 to 670 000 people in the United States alone are annually exposed to smoke from reported home fires. He further found² 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."

Today's fire safety professionals use diverse and *ad hoc* approaches to make these estimates, in part due to there being no widely accepted methodology of known accuracy for generating the smoke toxic potency data needed as input. There is a wide range of combustible items used in buildings. It is unrealistic to expect a comprehensive database of human or surrogate animal measurements of the smoke toxicity from real-scale burning of these items. Rather, data are commonly obtained from measurements of the toxic components of the smoke that are generated when test specimens are combusted in a bench-scale physical fire model.*

ISO TC92 SC3, Fire Threat to People and the Environment, has been preparing a suite of consensus International Standards, guides and calculation methods, along with instrumentation, measurement and validation procedures, for the analysis and assessment of the impact of fire and its effluents on people and the environment. It is a fundamental tenet of TC92 SC3 that data on the harmful effects of fire effluent are only to be used in the context of fire safety engineering, rather than being the basis for pass/fail tests for materials selection.³ Therefore, the charter of the Subcommittee also includes developing guidance on the use of such procedures in fire safety engineering, including the compilation of criteria for human exposure. Table 1 lists the documents currently in place or under development.

ISO 16312-1⁴ states that the role of a physical fire model for generating accurate toxic effluent composition is to "recreate the essential features of the complex thermal and reactive chemical environment in full-scale fires." These environments vary with the physical characteristics of the fire scenario and with time during the course of the fire, and close representation of some phenomena occurring in full-scale fires may be difficult or even not possible at the small-scale. The accuracy of the physical fire model, then, depends on two features:

* ISO/DIS 13943:2007, "Fire Safety - Vocabulary," defines a physical fire model as "a laboratory process, including the apparatus, the environment, and the fire test procedure, intended to represent a certain stage of a fire." ISO is the International Standards Organization.

1. The degree to which the combustion conditions in the bench-scale apparatus mirror those in the fire stage being replicated.
2. The degree to which the toxic potency obtained from burning of the commercial item at full scale is replicated by the toxic potency from burning specimens taken from the item in the bench-scale model. This measure is generally performed for a small set of items, and the derived accuracy is then presumed to extend to other test subjects.

Table 1. ISO TC92 SC3 Documents and Work Items (as of 4 April, 2007).

#	Title	Status
ISO 13344	Estimation of the Lethal Toxic Potency of Fire Effluents (Revision of ISO 13344:1996)	Published, 2004
ISO 13571	Life-Threatening Components of Fire – Guidelines for the Estimation of Time Available for Escape Using Fire Data	Published, 2007
ISO 16312-1	Guidance for Assessing the Validity of Physical Fire Models for Obtaining Fire Effluent Toxicity Data for Fire Hazard and Risk Assessment – Part 1: Criteria	Published, 2006
ISO/TR 16312-2	Guidance for Assessing the Validity of Physical Fire Models for Obtaining Fire Effluent Toxicity Data for Fire Hazard and Risk Assessment – Part 2: Evaluation of Individual Physical Fire Models	Published, 2007
ISO/TS 19700	Controlled Equivalence Ratio Method for the Determination of Hazardous Components of Fire Effluents	Published, 2007
ISO 19701	Methods for Sampling and Analysis of Fire Effluents	Published, 2005
ISO 19702	Guide for Analysis of Gases and Vapours in Fire Effluents Using FTIR Gas Analysis	Published, 2006
ISO 19703	Calculation of Species Yields, Equivalence Ratios and Combustion Efficiency in Experimental Fires	Published, 2005
ISO 19706	Guidelines for Methodology for Assessing the Fire Hazard to People	Published, 2007
PWI 26367-1	Guidelines for Assessing the Adverse Environmental Impact of Fire Effluents	NWIP ballot launched, 2007
PWI 26368	Guidance on Containment Systems for the Prevention of Pollution Arising from Uncontrolled Fire Water Run-off	PWI registered, 2005
DIS 27368	Analysis of Blood for Asphyxiant Toxicants – Carbon Monoxide and Hydrogen Cyanide	FDIS ballot, 2007
PWI 29903	Guidance for the Comparison of Toxic Gas Data from Different Tests	PWI registered, 2007
PWI 29904	Fire Chemistry – Aerosols Generation and Measurement in Fire	PWI registered, 2007
	Method Validation for Toxic Gas Analysis – Part 1: Limits of Detection and Quantification	PWI ballot launched, 2007

PWI: Preliminary Work Item
 NWIP: New Work Item Proposal
 AWI: Approved Work Item
 WD: Working Draft
 CD: Committee Draft

TR: Technical Report
 TS: Technical Specification
 DIS: Draft International Standard
 FDIS: Final Draft International Standard

An accuracy assessment of a physical fire model can be performed with and without the use of laboratory animals. Generally, accurate estimation of the toxic potency of the effluent can be obtained from analysis of a small number of gases (the N-gas hypothesis), as described in ISO 13571.

This is especially true for combustible item formulations similar to those for which the N-gas model has been confirmed. There are, however, cases where unusual toxicants have been generated in bench-scale apparatus. Thus, for novel commercial item formulations, confidence in the accuracy of the toxic potency measurement in the bench-scale device may be improved by a confirming bioassay and correlation with bioassay data from real-scale fire tests of the same combustible(s).

As presented in ISO/TR 16312-2⁵, there are numerous physical fire models in use today for generating some form of toxic potency information. The combustion conditions in these vary widely, and in general are not well characterized. There has been little rigorous validation of these apparatus; in fact, there is no standard protocol for performing such a validation. In addition, there is no standard protocol for obtaining a test specimen that will burn like the finished item from which it has been cut, nor is there quantitative information regarding the sensitivity of the toxic potency measurement to the conformation of the test specimen.

This paper presents a protocol for comparing the data from room-scale burning of a finished item with corresponding data generated using a physical fire model. It then demonstrates the process using room-scale and bench-scale data.

PROTOCOL FOR COMPARING TOXIC POTENCY INFORMATION

Several approaches to representing the toxic potency of fire effluent have been proposed or are in use.

Each of these could be considered a basis for one or more approaches to comparison of the output from bench-scale test apparatus to the output from a real-scale fire test. The approaches include:

- Lethality (LC₅₀ or IC₅₀) data for laboratory animals. This is the concentration of fire effluent, statistically calculated from concentration-response data, that causes death or incapacitation of 50 % of a population of a given species (typically laboratory rats) within a specified exposure time (typically 30 min) and post-exposure time (typically two weeks). Most of these data are for homogeneous materials, rather than specimens from finished items.⁶ Hazard or risk estimations can use these data in two ways.
 - Assumed average value. Reference 6 calculated mean LC₅₀ and IC₅₀ values, with experimental uncertainties, for the compiled literature data. For lethality, these included underventilated and well ventilated flaming combustion and oxidative pyrolysis. For incapacitation, there were only unambiguous data for the latter two combustion conditions. However, within these data sets, there were LC₅₀ and IC₅₀ values up to 20 times lower (i.e., more toxic) than the mean. Thus, the use of an average value in an estimation of available escape time could significantly overestimate that time.
 - Measured value for a specific combustible. As noted above, such data are available for few materials, and obtaining additional animal data is expensive and contrary to societal acceptability in some countries. There are also issues of extrapolation from rats to people and from 30 min exposures to the shorter exposure times for people who are actively evacuating a building.

Some combustion products, e.g., halogen acids, are lost to building surfaces as the effluent flows away from the fire. Thus, in both of the bulleted cases, there is a potential for overestimation of the potency of the fire effluent.

In addition, these measurements do not separate dose-based effects of the effluent from instantaneous effects.⁷

As a result, this paper addresses accuracy assessment based only on the yields of toxic species.

- Concentration of one or more combustion products. While the concentration of fire effluent is what people encounter as they move about a burning building, this is not a useful characterization of the production of effluent, or its hazard. The concentration is a function of the (time dependent) mass generation rate and the dispersion of that mass into a volume. The magnitude of the volume and the air flow through that volume determine the concentration as much as the source term. This is also true in a physical fire model. It is more proper to characterize the effluent by the set of yields (mass of a combustion product per mass of consumed fuel) of the components, separating out transport and dilution effects.
- Yield of carbon monoxide. This presumes that, as is often stated, CO is the dominant toxicant. Data indicate that it is indeed almost always a significant component of the toxic potency of fire effluent. However, there are fire tests, e.g., in Reference 8, that have shown other toxicants, e.g., HCN and HCl, to be at least as important for some combustibles. Thus, when evaluating a physical fire model, the yield of CO must be included in the comparison with real-scale test data, but it should not be the only consideration.
- Yields of significant toxic combustion products. This is the technically strongest approach for determining physical fire model accuracy. It is the focus of ISO 16312-1 and the current work.

The following are considerations for the validation process based on the yields of toxicants generated during the burning of a combustible or a test specimen cut from it.

- The accuracy assessment should be performed for each of the fire stages (ISO 19706³) needed for fire safety engineering. An assessment for one such stage is not necessarily sufficient for appraising the value of a physical fire model for a different fire stage. There may also be multiple real-scale fires of reference for a given fire stage.
- The combustion conditions in the physical fire model should be consistent with those in the real-scale fires of reference. Characterizations such as “well ventilated, pre-flashover” or “post-flashover” may be sufficient. The use of equivalence ratios helps to quantify these terms. However, care must be exercised not to over-rely on this descriptor. Virtually all combustors, bench-scale and room-scale, are characterized by *global* equivalence ratios. The combustion conditions (e.g., gasification rate, oxygen availability, and mixing) are rarely uniform along the surfaces of the test specimen and are represented by an overall average. Two systems with the same calculated global equivalence ratio still are likely to have some differences in the regions where the combustion products are actually determined.
- The specimens tested at both scales must be composed of the *same* materials. All materials with the same generic name are not the same. For example, materials designated as “polyurethane foam” or “wood” can have different chemical compositions and burning behaviors, potentially resulting in different yields of toxic combustion products. For combustibles consisting of multiple materials (e.g., a sofa), bench-scale test specimens cut from the full item should have all the materials present in a similar proportion by mass and in a similar conformation, until it is demonstrated that the yields of toxicants are not sensitive to the conformation of materials in the test specimen.
- The list of measured toxicants should include those that are first-order contributors (i.e., each accounting for at least 20 % of the smoke potency) and (some) second-order contributors to the undesired outcome, e.g., incapacitation or death.
 - For the first-order toxicants, a quantitative comparison is necessary between the yield data from the physical fire model and the data from the room-scale fires.
 - The contributions of second-order toxicants should be the same at both scales, e.g., a toxicant whose estimated contribution to incapacitation at room-scale is negligible should also be a negligible contributor to incapacitation from the mix of toxicants generated in reduced scale.

- The list of toxicants should include chemicals that indicate differing extents of oxidation of the materials in the tested item. For example, for the carbon in nearly all combustibles, the list might include CO₂, CO, and acrolein (decreasing order of oxidation). For nitrogen-containing items, the list might include NO₂ and HCN.
- The sufficiency of the degree of agreement between scales is derived from the tolerable uncertainty in the calculations of the safe available egress time. Uncertainties in the experimental measurements (at both scales) may limit the precision of the comparison.

The following is the sequence of steps used to obtain a comparison in this study.

- Combust samples of these specimens in the bench-scale device under a range of combustion conditions appropriate for well-ventilated and underventilated fires.
- Determine whether the principal toxicants are the same at both experimental scales, using the equations in ISO 13571. For CO, other room-scale studies have measured post-flashover yields significantly larger than the values determined here (see below).
- Determine whether the toxicants that were second-order in toxicological importance in the room-scale tests are also secondary in the bench-scale effluent.
- For the gases whose yields were below the detection limits in the room-scale tests, determine whether the bench-scale results are consistent with those detection limits.
- Determine the degree of agreement between the room-scale yields and the bench-scale yields of the principal toxicants, as well as the calculated LC₅₀ and IC₅₀ values. ISO 16312-1 provides some guidance regarding desirable degrees of agreement. Additional guidance can be obtained by performing a set of hazard analyses and determining the sensitivity of the available escape time to the uncertainties in the yield data.

In this preliminary report, only the first four steps are included.

ROOM-SCALE FIRE TESTS

Test Description

NIST has reported on room-scale tests for both pre- and post-flashover burning of three finished items, which were selected for diversity of physical form, combustion behavior, and the nature and yields of toxicants produced.⁸ Each item was compositionally complex and presented a challenge to the extraction of a representative specimen for testing at reduced scale.

- “Sofas” made of upholstered cushions supported by a steel frame. The fire retardant in the cushion padding contained chlorine atoms. Thus, this fuel would be a source of CO₂, CO, HCN, nitrogen oxides, HCl, and partially combusted organics.
- Particleboard bookcases with a laminated polyvinyl chloride (PVC) finish. This fuel would be a source of CO₂, CO, partially combusted organics, HCN, nitrogen oxides, and HCl.
- Electric power cable in a three-dimensional array of horizontal trays. This fuel would be a source of CO₂, CO, HCl, HCN, nitrogen oxides, and partially combusted organics.

Briefly, the three combustibles were burned in a room whose only vent was a doorway leading to a corridor; the downstream end of the corridor was unconfined. A schematic is shown in Figure 1 and a photograph in Figure 2. Gases and soot were sampled at some or all of the four locations noted in Figure 1. The probes for Fourier transform infrared (FTIR) analysis were approximately 10 cm upstream of the probes for fixed gas analysis. All the data used for the gas yields reported in this paper were calculated from data taken at location 2. There, the tips of two probes were located nominally 1 m outside the burn room doorway and 30 cm from the ceiling. The distance from the doorway was selected to be where minimal entrainment of corridor air and dilution of the combustion

products would have occurred following their leaving the burn room. The distance from the ceiling was selected to avoid sampling from within a stagnant boundary layer but still capture combustion products from early, low-momentum effluent flows. For the more intense post-flashover fires, the flames were not always fully quenched at these locations.

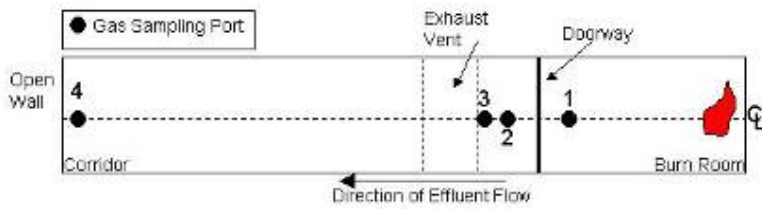


Figure 1. Schematic of Test Room and Corridor.



Figure 2. Photograph of Test Corridor, Showing Opening to the Fire Room and the Vent in the Ceiling.

There were two types of tests:

- The first type was used to scope the burning behavior of the fuel and to guide the protocol for the second type of tests. A large vent in the corridor ceiling enabled measurements of CO_2 , CO and O_2 concentrations to be made in the exhaust duct for heat release rate determination.⁹ Mass flow and temperature were also measured in the exhaust duct.
- The second type of test was used to determine the yields of a set of toxic gases: CO , CO_2 , HCl , HCN , NO , NO_2 , acrolein, and formaldehyde. The needed, time-dependent measurements were the concentrations of these gases, the remaining mass of the combustible, the door area through which the flow exited the burn room, the temperature and density of that flow, and the pressure differential across the doorway.

Oxygen measurements were made using paramagnetic analyzers. CO and CO_2 concentrations were measured using nondispersive infrared (NDIR) analyzers, with the gases sampled through unheated copper lines. Gases were sampled through PTFE lines heated to 170°C for measurement of all gases (except O_2) using FTIR spectrometers. There were no soot filters in the FTIR transfer lines since these also collect acid gases. While the acid gases can be extracted and analyzed after the test is over, one only obtains an integrated mass of each compound, and the objective of this study required time-resolved (at least pre- vs. post-flashover) concentration information. The optical path lengths in the FTIR cells were nominally 10 cm. While a cell of multi-pass optical path offered higher sensitivity, such a cell had internal mirrors, which were damaged by the unfiltered fire effluent. The smaller cell with a smaller volume offered better robustness and time resolution, an important issue when the combustion conditions in the fire were changing during a test. The minimum detection limits in these room-scale tests are listed in Table 2.

Figure 3 shows indicative placement of the test specimens in the burn room. The sofas and bookcases were ignited using the burner for testing mattresses under California Technical Bulletin 133.¹⁰ The electrical cable arrays were ignited using two 152 mm square, sand-filled steel propane burners.

Table 2. Minimum Detection Limits Using FTIR Spectroscopy.

Compound	Minimum Detection Limit ($\mu\text{L/L}$)
Acrolein ($\text{C}_3\text{H}_4\text{O}$), CO	10
Formaldehyde (COH_2)	50
CO_2	5
HCN, HCl	15
NO	500
NO_2	100

Figure 3. Photographs of Combustibles in the Test Room. (The bookcases were oriented facing each other to maximize radiative feedback during ignition, as the bookcases were resistant to ignition and sustained burning at low flux levels.)



SOFA



BOOKCASES



CABLE

Once independent burning of the combustible was established and the fire effluent was actively flowing out of the room of origin, pre-flashover gas measurements were initiated. These continued for two to three minutes or until it appeared that flashover was approaching. Flashover generally coincided with flaming of paper placed on the floor of the fire room. Post-flashover data were also collected for 2 min to 3 min.

Two of the sofa tests were conducted with the doorway blocked, simulating a ventilation-limited fire that would not proceed to flashover due to an insufficient supply of oxygen.

Room-scale Test Results

Table 3 compiles the calculated yields of the measured toxicants, along with the experimental uncertainties in those values. The latter figures include repeatability and measurement uncertainty, with the experimental repeatability being the larger component.

For nearly all combinations of combustible and fire stage, the combination of yields of CO, CO_2 , and soot (not described here) accounted for the bulk of the carbon lost from the combustibles during the fires. The one exception was the pre-flashover burning of the bookcases. Similarly, the yields of HCl were close to the notional yield for the bookcase fires and the post-flashover sofa fires. The HCl yield was high for the pre-flashover sofa fires, perhaps indicating a disproportionate release of the fire retardant during the early burning. The HCl yields for the cable fires were low relative to the notional yield, indicating the effectiveness of the filler at scavenging HCl or loss of the HCl to the walls of the fire room.

Table 3. Yields of Combustion Products from Room-scale Fire Tests (g/g).

Gas	Fire Stage	Sofa	Bookcase	Cable
CO ₂	Pre-flashover	1.59 ± 25 %	0.50 ± 50 %	0.120 ± 45 %
	Post-flashover	1.13 ± 25 %	1.89 ± 75 %	1.38 ± 15 %
CO	Pre-flashover	1.44 x 10 ⁻² ± 35 %	2.4 x 10 ⁻² ± 55 %	5.5 x 10 ⁻³ ± 50 %
	Post-flashover	5.1 x 10 ⁻² ± 25 %	4.6 x 10 ⁻² ± 30 %	1.48 x 10 ⁻¹ ± 15 %
HCN	Pre-flashover	3.5 x 10 ⁻³ ± 50 %	4.6 x 10 ⁻⁴ ± 10 %	6.3 x 10 ⁻⁴ ± 50 %
	Post-flashover	1.5 x 10 ⁻² ± 25 %	2.5 x 10 ⁻³ ± 45 %	4.0 x 10 ⁻³ ± 30 %
HCl	Pre-flashover	1.8 x 10 ⁻² ± 30 %	2.2 x 10 ⁻³ ± 75 %	6.6 x 10 ⁻³ ± 35 %
	Post-flashover	6.0 x 10 ⁻³ ± 35 %	2.2 x 10 ⁻³ ± 65 %	2.1 x 10 ⁻¹ ± 15 %
NO ₂	Pre-flashover	< 7 x 10 ⁻²	< 2 x 10 ⁻²	< 4 x 10 ⁻³
	Post-flashover	< 1 x 10 ⁻³	< 1 x 10 ⁻³	< 1 x 10 ⁻³
Acrolein	Pre-flashover	< 8 x 10 ⁻³	< 2 x 10 ⁻³	< 4 x 10 ⁻⁴
	Post-flashover	< 1 x 10 ⁻⁴	< 1 x 10 ⁻⁴	< 1 x 10 ⁻⁴
Formaldehyde	Pre-flashover	< 2 x 10 ⁻²	< 2 x 10 ⁻³	< 8 x 10 ⁻⁴
	Post-flashover	< 8 x 10 ⁻⁴	< 4 x 10 ⁻⁴	< 7 x 10 ⁻⁴

A number of room-scale fire studies have indicated that the yield of CO is approximately 0.2 and that this value is not very dependent on the combustible.¹¹ In this study, the post-flashover CO yields from the cable fires approached this, with a mean of *ca.* 0.15 g/g. The sofas and bookcases appeared to generate about one quarter of the expected value. The rooms clearly reached flashover, and the FTIR and NDIR analyzers produced comparable CO yields. Thus, the most likely reason for the low CO yields is oxidation in the secondary burning beyond the doorway.¹² Different fires and different stages of those fires are likely to be accompanied by differing degrees of CO formation and burnout. Thus, the authors of Reference 8 suggested that for fire hazard and risk assessments, one should use the CO yield value of 0.2 g CO per g fuel consumed. For assessing the accuracy of the data from such apparatus, it is also appropriate to use the CO yield value of 0.2 g CO per g fuel consumed.

The equations in ISO 13571 for use in estimating the time available for escape from a fire include additional sensory irritants that were measured here: NO₂, C₃H₄O, and H₂CO. Their presence was not detected, thus establishing the upper limits of their volume fractions at 100 µL/L, 10 µL/L, and 50 µL/L, respectively.

All three of these gases are sensory irritants. Their incapacitation concentrations from ISO 13571, their post-flashover volume fractions normalized to that of HCl in this study are shown in Table 4. (The measured pre-flashover concentrations were too low to obtain usable comparisons.) From this analysis, the maximum concentrations of NO₂, formaldehyde and acrolein that could have been present would have had secondary contributions to incapacitation relative to the concentration of HCl in the sofa and cable tests. In the bookcase tests, where the HCl levels were low, the other irritants could be important relative to HCl. However, the high levels of CO in those tests suggest a secondary role for the irritant gases in causing incapacitation.

Table 4. Limits of Importance of Undetected Toxicants.

	Volume Fraction, $\mu\text{L/L}$				<u>Toxicant Volume Fraction</u> Volume Fraction of HCl			
	HCl	NO ₂	C ₃ H ₄ O	H ₂ CO	HCl	NO ₂	C ₃ H ₄ O	H ₂ CO
Incapacitating Level ⁷	1000	250	30	250	1.00	0.25	0.030	0.25
Sofa	800	< 100	< 10	< 50	1.00	< 0.12	< 0.012	< 0.06
Bookcase	20 to 200	< 100	< 10	< 50	1.00	< 5 to 0.5	< 0.5 to 0.05	< 2.5 to 0.25
Cable	1400	< 100	< 10	< 50	1.00	< 0.007	< 0.0007	< 0.04

The calculated global equivalence ratios (calculated from the air flow into the room through the lower portion of the doorway and the mass loss from the burning item) ranged from about 0.05 to 0.25 for the pre-flashover fires and from 0.18 to 0.44 for the post-flashover fires. While these values might be interpreted as meaning that all the fires were fuel-lean, computational fluid dynamics modeling of similar enclosure fires indicated that some of the air enters the room through the lower portion of the doorway and is immediately pushed out the upper portion of the doorway without reaching the fire zone. This reinforces the need to treat global equivalence ratios with caution.

PHYSICAL FIRE MODEL

The physical fire model used was that in NFPA 269/ASTM E1678.^{11,13} A photograph of the apparatus is shown in Figure 4. The test specimen is located in the cylindrical quartz tube in the lower left corner. The standard procedure calls for exposing a test specimen (surface up to 76 mm x 127 mm, up to 50 mm thick) to an irradiance of 50 kW/m² for 15 min, then turning off the lamps and waiting another 15 min. During burning, the effluent rises through a chimney into the clear plastic chamber, while chamber air is forced back to the fire zone, recycling the air supply for combustion. Based on the concentrations of toxicants in the chamber, the FED[†] is calculated, using an N-gas equation for a 30 min exposure of laboratory rats. The specimen size is then adjusted and the test repeated until the calculated FED is approximately unity. There is little guidance on the preparation of the test specimen, except that it “represent the end-use product.”

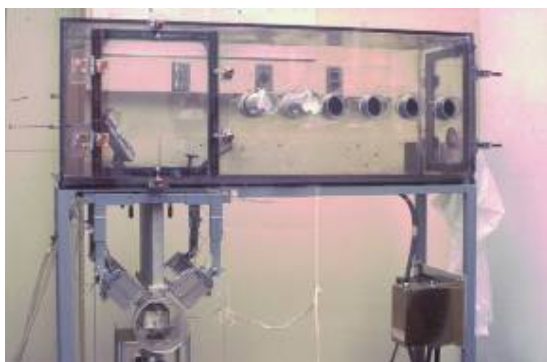


Figure 4. Photograph of the NFPA 269/ASTM E 1678 Radiant Furnace Apparatus.

A limited prior accuracy assessment¹⁴ of this apparatus for post-flashover room fires had indicated agreement of LC₅₀ values to within a factor of 2, after adjusting the bench-scale CO yield to 0.2 g/g,

[†] The fractional effective dose, FED, is the ratio of the actual dose of smoke to the dose expected to result in a specified effect on an exposed person of average susceptibility.

in accord with the findings noted above from Reference 11. The principal toxicants were the same, if one accounted for differences in oxygen concentration (a term in the N-gas equation) and sampling losses of HCl between the two test apparatus. The N-gas equation predicted the results of the tests to within a factor of two or better. However, there were some discrepancies in the values of some toxicant yield values. Overall, the apparatus predicted the room-scale results within a factor of 3. For a small, developing fire, the bench-scale specimen is described as a “reasonable representation of the full-scale fire.”¹¹

In the current test series, test specimens from the three combustible items from Reference 8 were examined as prescribed in the ASTM Standard. The test specimens were prepared as follows:

- “Sofas:” A layer of the upholstery fabric was laid on a slab of the foam padding. The sides and bottom were covered with aluminum foil. The effects of doubling the fabric layer and of dicing the foam and fabric were also examined.
- Bookcases: Testing was conducted with a single slab. Alternate testing used the same mass of material that had been diced into smaller pieces.
- Electric power cable: 120 mm long cuttings of the intact cable were tested first. Then, diced samples of the same mass were tested.

A set of tests was conducted with the initial volume fraction of oxygen in the chamber at approximately 0.205, namely ambient air. Vitiation occurred during the latter portion of the pre-flashover stage of the room fires and into the post-flashover stage. To determine whether a better fit to the room-scale gas yields were possible under technically reasonable combustion parameters, bench-scale tests were also conducted under a reduced initial oxygen concentration of 0.17. Below that, it was difficult to get all the specimens to ignite. All tests were performed at a nominal irradiance 50 kW/m².

Chamber air was extracted continuously, dehydrated, filtered, and flowed through fixed gas analyzers for CO₂, CO and O₂ before being returned to the chamber. A second flow was extracted from the chamber through a 170 °C heated line to an FTIR spectrometer similar to the one used in the room-scale tests. This flow was also returned to the chamber following passage through the FTIR cell. The sample mass and chamber temperature were monitored continuously.

There were some changes to the test procedure that will be discussed in a future paper. One significant modification altered the combustion duration. It was observed that the specimen flaming was generally complete in well under the standard 15 min exposure of the test specimen to the radiating lamps. For a specimen whose residue was prone to radiative pyrolysis, the standard exposure led to combustion products from two stages of a fire. Therefore, upon cessation of flaming, the chimney was capped, isolating the chamber gases from contributions from any continued specimen degradation.

COMPARISON OF RESULTS

The following are preliminary comparisons of yield data between the post-flashover results from the room and the results from the bench scales:

Under the standard operating conditions (uncut test specimen, O₂ volume fraction about 0.205), the following are partial results:

- “Sofa:” The major toxicants were CO and HCN at both scales of test. HCl was a secondary toxicant at both scales. The CO₂ yields were in good agreement. The bench-scale CO yields were lower by about a factor of 2.
- Bookcase: The major room-scale toxicants were CO and HCN. In the bench-scale tests, the HCN yields were insignificant. The HCl yield was near the measurement limit, indicating it

was toxicologically insignificant, in agreement with the room test results. The bench-scale CO₂ yields were about a factor of 2 lower, suggesting a higher char yield. The bench-scale CO yields were about a factor of 3 lower, similar to pre-flashover yields from the room tests.

- Electric power cable: The major toxicants at both scales were CO, HCl, and HCN. The CO₂ yields were only slightly lower than those from the room tests.

Varying the test conditions, the following partial results were observed:

- Dicing the test specimens led to no or small (< 30 %) reduction in the ratios of yields (R) of CO₂ to CO for all of the items.
- Reducing the initial oxygen volume fraction also led to no or small (< 30 %) reduction in the ratios of yields (R) of CO₂ to CO for all of the items, whether the specimen was intact or diced.
- Combinations of reduced initial oxygen concentration and dicing of the specimen did not always lead to additive reductions in R.

STATUS

A full assessment of the accuracy of this physical fire model awaits a more complete analysis of the results. Next, this process will be repeated for three additional physical fire models: a tube furnace, ISO/TS 19700; the cone calorimeter, ISO 5660-1; and a closed box combustor, ISO 5659-2.

ACKNOWLEDGEMENTS

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